SATELLITE-TRACKING AND EARTH DYNAMICS RESEARCH PROGRAMS

Grant Number NGR 09-015-002

Semiannual Progress Report No. 48

1 January to 30 June 1983

Prepared for

National Aeronautics and Space Administration
Washington, D.C. 20546

September 1983

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Mr. David L. Townley, Code TN-1, Network Operations, Office of Space Tracking and Data Systems, NASA Headquarters, Washington, D.C. 20546.

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TABLE OF CONTENTS

SATELLITE TRACKING RESEARCH PROGRAM IN SOLID-EARTH GEOPHYSICS

Semiannual Progress Report No. 48

1. INTRODUCTION AND SUMMARY

This report describes the activities carried out by the Smithsonian Astrophysical Observatory (SAO) for the National Aeronautics and Space Administration (NASA) under Grant NGR 09-015-002 during the period 1 January to 30 June 1983. Work on geodesy, geophysics and the upper atmosphere are currently funded separately from this grant, although that research is still maintained as part of a total integrated program at the Observatory. Reports related to this are included in Appendix 1.

The SAO laser in Arequipa was in routine operation during the reporting period. The laser, which was upgraded in FY 1982, continues to operate at the specified level. Range noise is typically 12-18 cm on Lageos and 6-15 cm on the low orbiting satellites. Accuracy is estimated at 3-5 cm based on detailed ground based measurements.

The Arequipa station obtained a total of 31,989 quick-look range observations on 719 passes in the six months. In addition, routine participation by cooperating networks contributed greatly to the success of ongoing tracking campaigns. Data were acquired from Metsahovi, San Fernando, Kootwijk, Wettzell, Grasse, Simosato, Graz, Dodaira and Herstmonceux (see Table 1).

During the reporting period work progressed on the setup of SAO 1 in Matera, Italy. The building construction was completed and the installation of the laser equipment is near completion. We anticipate that the station will be operational by August 1983.

Discussions were also initiated with the Israelis on the relocation of SAO-3 to a site in southern Israel in FY 1984. In anticipation of such a relocation the SAO-3 laser is now being upgraded in Cambridge.

Arequipa and the cooperating stations continued to track LAGEOS at highest priority for polar motion and earth rotation studies, and for other geophysical investigations, including crustal dynamics, earth and ocean tides, and the general development of precision orbit determination. At lower priority, BE-C and Starlette were tracked for refined determinations of station coordinates and the earth's gravity field and for studies of solid earth dynamics.

During this reporting period, SAO completed the revisions to its field software as a part of its recent upgrading program. An IRV capability was incorporated into the SAO prediction cycle and work was completed on the modifications to manuals and documentation to reflect the upgrading changes to hardware, software and operations.

Cesium standards and Omega receivers provided on long-term loan by the U.S. Coast Guard continue to function well at Arequipa. With these and other timekeeping aids, the station has been able to maintain a timing accuracy of better than plus or minus 6 to 8 microseconds.

The communications links with Arequipa, Peru have continued to operate satisfactorily. A computer-to-computer link via radio was instituted to facilitate the large volumes of quick-look traffic.

Data Services provided final data to the National Space Science Data Center for the period through April 1983. Final data are now being furnished on a routine basis 60 days after the end of the acquisition month (see Table 2). Most of the software activity was focussed on the refinement of the field software for the greater operator effectiveness and the improvement of field diagnostics.

The minicomputer-to-VAX link in Cambridge continued to function well. The minicomputers are now routinely used as interactive terminals and as remote data-entry devices. They provide Data Services and other support groups with a remote-batch capability and facilitate the processing of quick-look data.

2. OPERATING STATUS

During the reporting period, the laser in Arequipa tracked 719 satellite passes, of which 234 were Lageos. Lageos passes averaged 200 points per pass with some passes over 700 points. Arequipa obtained 210 passes of BE-C and 275 passes on Starlette. Weather continued unusually clear for the normally cloudy period in January and February but turned cloudy in April. The station's operational success rate was nearly 70% for this six month period (see Table 3). Out of a total 1172 passes predicted, only 73 (5%) were lost due to equipment malfunction.

Table 1.

Quick-look passes and points, 1 January through 30 June 1983

Station	January		Feburary		March		April		May		June		Total	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
Arequipa	104	4722	86	3293	60	2175	102	4128	203	9698	164	7973	719	31989
Metsahovi					5	121	2	43					7	164
San Fernando	11	621	1	17	20	1098	8	351	4	68	20	620	64	2775
Kootwijk	2	30	20	382							6	89	28	501
Wettzell			16	549	5	189	5	131	2	63	4	100	32	1032
Grasse	35	1092	16	513	14	461	14	450	4	129	2	78	85	2723
Simosato	43	1850	17	608	12	418	5	85	12	174	24	493	113	3628
Graz	13	257	2	112	12	281	10	241	1	25	26	600	64	1516
Dodaira					4	45							4	45
Herstmonceux							4	141			5	159	9	300
TOTAL	208	8572	158	5474	132	4788	150	5570	226	10157	251	10112	1125	44673

Satellite	January		Feburary		March		April		May		June		Total	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
BE-C	56	2420	31	1224	29	1226	24	966	78	3266	86	3408	304	12510
Starlette	66	2431	56	1713	38	1343	67	2366	79	3619	100	3735	406	15207
LAGEOS	86	3721	71	2537	65	2219	59	2238	69	3272	65	2969	415	16956
TOTAL	208	8572	158	5474	132	4788	150	5570	226	10157	251	10112	1125	44673

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Table 2.

Final Data Statistics - Arequipa Peru

January-June 1983 Passes/Points

Satellite	Jan		Feb		Mar		Apr		May		June		Total	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
BE-C	29	1505	29	1494	8	223	18	864	70	5159	52	3335	206	12580
Starlette	42	2645	33	1618	20	1177	45	2240	71	5772	59	5108	270	18560
LAGEOS	29	4675	23	2511	27	1832	36	3512	59	13606	58	16182	232	42318
Arequipa Peru TOTAL	100	8825	85	5623	55	3232	99	6616	200	24537	169	24625	708	73458

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Table 3.

Laser operations summary, 1 January through 30 June 1983

Station	Passes Scheduled	Passes Supported	Data Obtained*	Passes cancelled owing to: Weather**	System Down	Other
Arequipa	1352 (100%)	1002 (74%)	722 (67%)	272 (20%)	73 (6%)	5 (0%)

* Number of passes and percent of total scheduled minus passes canceled because of weather.

** Not included are passes attempted but unsuccessful because of poor weather.

3. LASER OPERATIONS AT COOPERATING AGENCIES

The following foreign cooperating sites were active and provided quick-look data on a regular basis during the reporting period: Simosato, Japan; Grasse, France; Graz, Austria; and San Fernando, Spain. The first three sites are second generation laser systems which provided high quality data. San Fernando, Spain provided one meter data on a regular basis. The San Fernando site will be closed down during the second half of 1983 to undergo upgrading, as will the laser presently operated at Grasse, France, which will also be closed during the next reporting period for upgrading. The sites in Kootwijk, Netherlands and Wettzell, Germany operated for part of the reporting period but were not as active as in the past due to weather and equipment problems. The stations in Metsahovi, Finland and Dodaira, Japan provided some data during the period, and a new site at the Royal Greenwich Observatory in Herstmonceux, England became operational in April. We hope this site will be very active during the MERIT campaign. The system is a third generation laser with capability for 3 cm accuracy.

4. SATELLITE OBSERVING CAMPAIGNS

SAO continued its program of data acquisition, with particular emphasis on follow-up support for the preliminary MERIT Campaign and preparation for the full MERIT Campaign to start in September. In addition, satellite observations were made to:

A. Support the scientific and orbital maintenance requirements for LAGEOS and the Crustal Dynamics Program;

B. Support the study of earth body and ocean tides, seasonal and other variations in the earth's gravity field, and the investigation of polar motion;

C. Provide data for improving the accuracy of station coordinates and the gravity-field model, which are necessary for LAGEOS and other geophysics programs; and

D. Support the tracking campaign for Starlette in conjunction with CNES.

With the success of the preliminary MERIT Campaign in 1980, work continues on a routine but informal interim basis to keep continuous tracking coverage on LAGEOS and Starlette and to continue the routine calculation of pole position from all available quick-look data. This is particularly important for all investigations involving long period effects such as the annual and Chandler effects.

5. OPERATIONS AND MAINTENANCE ENGINEERING

The Engineering Group of the Experimental Geophysics Department provides the daily hardware and systems support necessary to maintain routine network operations. It is also responsible for the system modifications and improvements required for new programs.

5.1 Laser and Photoreceiver

In May, the data from Arequipa showed an increase in range noise and a small range offset (0.2 - 0.3 nanoseconds) at the 1-2 photoelectron level. Through systems tests the difficulty was traced to a decrease in the threshold of the Constant Fraction Discriminator in the Start Channel Electronics. The threshold was reset and now is monitored on a weekly basis.

Within the same timeframe, a gradual decrease in return signal strength was also noted by the field crew. This difficulty was traced to the 3 Angstrom filter in the photoreceiver which had drifted from its center frequency. The filter was thermally retuned for peak response giving a 3:1 improvement in signal strength. The problem has been attributed to aging of the filter crystal. A spare 3 Angstrom filter and controller was sent to the station as a back up. A tuning curve for the filter will be run monthly to verify the peak setting of the temperature controller. In June the filter test was rerun showing that the filter is still drifting slowly. Once the replacement filter is installed, the original filter will be returned to the manufacturer for evaluation.

Thin film polarizers purchased in the past from Optical Coating Laboratory Inc. (OCLI) and Trans World Optics exhibited early coating failure, and alternative manufacturers were investigated. Two off-the-shelf polarizers from CVI Laser Corporation, which did not quite meet our mechanical size specification, were tested at SAO-2 and found acceptable. As a result, twelve customized polarizers were ordered from CVI and arrived in mid-May. Four of the twelve polarizers failed incoming inspection due to defects in the coating. These were returned to the manufacturer. Of the remaining eight polarizers, four were sent to Arequipa and four to Matera.

Daylight ranging was tried on Lageos with some success, particularly during twilight hours. A software modification was made to the Direct Connect program to allow range gate window changes at the operators discretion during a pass. This new feature will allow the operator to start the pass with a large range gate window, and once the satellite is acquired and optimized for early/late along-track corrections, to narrow the window and greatly reduce the daylight-caused noise stops. This software package is en route to Arequipa and will be installed in July.

Two continuing problems in the Arequipa laser system have been: (1) the rapid degradation of Pockels cells and (2)the leakage thru the Pockels cell before and after chopping. The degradation of the cells is an operational problem that requires cells to be changed every 3-4 months depending upon useage. The leakage problem, which is exacerbated at short pulse widths, is currently limiting us from reducing pulse width below the present 3 nsec FWHA pulse.

To alleviate these problems, two new Pockel cells were ordered from an alternative manufacturer, Cleveland Crystals. These new cells, which have been adapted as direct replacements from our current cells, arrived in late March and after acceptance testing were sent to Arequipa and Matera. The new cell was installed in Arequipa in mid June and is now operational. The leakage has been reduced by about a factor of 2-3; tests are still underway to determine if the leakage can be further reduced.

PMT lab tests were run this spring to study and hopefully optimize the time-related characteristics of the EMI 2233B PMT. A shortened version of our findings has been included as Appendix 2 of this report.

In this study, the time related characteristics were measured. It was determined that for an optimum aperture diameter of 24 mm of the PMT photo cathode and a bias voltage of 2200V, transit time jitter was 0.4nS. A light source of 100 picoseconds was used for this test. It was also verified using these findings that our system would not be PMT limited until the source pulse width reaches 1.0 nS. Realistically, the narrowest pulse width we can obtain from our present ruby Q switch, pulse chopper system is 1.5 nS.

5.2 Data System and Pulse Processor

Further work was done on the Analog Detector in an effort to improve ranging accuracy by increasing circuit speed and providing a better pulse shape match. Using a Tektronix 7S12 Time Domain Reflectometer, the circuit reactance and characteristic impedance of the strip line in the matched filter and differentiator were optimized for minimum signal reflection. A small improvement of 50-100 pS in the slope of zero cross detection sensitivity was achieved.

Various strip line layouts in the Matched Filter were tried to reduce circuit capacitance and increase circuit bandwidth. Using a relatively simple modified strip line and ground plane layout, the operating bandwidth of 600 MHz can be increased to 800 MHz. However, the bandwidth of the overall Analog Detector is still constrained to 500 MHz by a commercially available signal splitter (8-1) and a wide band amplifier used in the Analog Detector. At this time, the increase in bandwidth was not deemed significant enough to warrant the purchase of higher bandwidth splitters and amplifiers. However, if the laser pulse width is reduced to 2nS, then the availability of suitable units must be investigated.

An examination of the Arequipa laser pulse showed it approached a triangular (isosceles) instead of Gaussian shape, which was the original basis of the matched filter design. The filter was redesigned to match the triangular shape and then tested in the lab. The test, using a laser diode, a XP2233B PMT and a fiber optic optical path showed that system response in the 1-30 Pe range could be improved by about 30% with the reworked filter. Modified units have been sent to Arequipa for field

trials.

By the end of June work was completed on the re-writing of the laser system documentation to reflect recent upgrading. Extensive revisions and re-issues were made to the existing manuals along with the issue of several new manuals. Printing of the last two new manuals will be completed by August.

In late May the SAO-3 laser equipment arrived from Australia. All the chassis to be upgraded have been removed from the boxes and work is well underway with completion scheduled for the end of July. Some damage was sustained by the power supply transformers for the laser control chassis in shipment from Australia. The transformers, each weighing 300 lbs., had broken loose in the packing case causing some damage. Fortunately, the damage could be repaired, and the transformer passed electrical check-out by the manufacturer.

An old Rubidium frequency standard was repaired and tested. This unit is functional, has good long term stability, but does not quite meet its original specifications for short term stability. A major redesign would be necessary to correct this problem. It is intended to use this unit as a back up clock in the SAO 3 system until an additional timing standard can be made available.

5.3 Routine Engineering

A new cooling unit shipped to Arequipa in late 1982 finally arrived at the station and has been installed in the crystal cooling loop. This change allows the original unit to be dedicated to the flashlamp cooling loop for increased cooling required by the new higher repetition rates of the laser.

5.4 Minicomputers

The communications minicomputer system was overhauled. The older NOVA 1200 was replaced with a refurbished NOVA 1200, and a third Linc tape drive was added to the system.

The radio data communications was switched from baudot teletype to ASCII minicomputer-to-minicomputer based data communications. A new radio data interface and a new communication minicomputer program permit the direct minicomputer-to-minicomputer exchange of ASCII data over the radio from the Arequipa station.

We experienced several minicomputer system failures in Cambridge and Peru. All of these failures were repaired within 24 hours. No down time was incurred in any of these failures because sufficient spare parts were available.

In Cambridge, a series of apparent minicomputer malfunctions was finally identified as a software problem. The problem was the accidental substitution of an old Linc Tape Operating System (LTOS) version for our current LTOS version.

The software for the Cambridge minicomputer system nine-track magnetic tape drive was completed and the nine-track tape drive was placed in service (see Section 7.3, NOVA Nine-Track Software).

5.5 Timekeeping

During the reporting period, timekeeping systems for the Peru tracking station have maintained epoch time traceable to UTC (US Naval Observatory reference) with an accuracy of at least plus or minus 8 microseconds. The station clock at Arequipa and the one being set up at Matera are each equipped with a broad-based timing system comprised of dual parallel timing channels. Cesium or rubidium oscillators, backed up by rubidium oscillators, offer a stable time base for each channel. Redundant time accumulators guard against time discontinuities, and redundant VLF/OMEGA receivers provide a reliable backup and frequency reference for the system. Portable clock comparisons are required to provide the necessary epoch reference checks until a satellite-based time transfer system can be implemented.

No portable clock trips were needed during the time period. One is being scheduled for Matera in July. One will be required during the next half year for Peru.

OMEGA time data is being collected at SAO headquarters and Peru for the US Coast Guard for input into their global OMEGA transmission model. OMEGA is used for a primary frequency reference for the Peru site.

Timing equipment was prepared and shipped to Matera, Italy, for installation which was completed in June. A rubidium oscillator was repaired for use in that system.

Note Table 4 titled, "SAO Network Timekeeping Status for January 1983 thru May 1983."

Table 4

SAO NETWORK TIMEKEEPING STATUS for January 1983 thru May 1983

Definitions:

(STAT - UTC) = epoch range of SAO field station main clock a positive quantity means station clock ahead of UTC as maintained by the US Naval observatory (USNO)

REDUCTION UNCERTAINTY = estimated absolute error of reduced station time during the period specified. Future clock comparisons may lower this uncertainty value.

EPOCH SET UNCERTAINTY estimated epoch time transfer accuracy

LAST COMPARISON the last portable clock comparison on site Cs refers to cesium portable

STATION	REDUCTION PERIOD from	thru	(STAT - UTC) RANGE microseconds	REDUCTION UNCERTAINTY <+/-microseconds	EPOCH SET UNCERTAINTY <+/-microseconds	LAST COMPARISON by	when
EGYPT	Jan 1 83			50		Czech/Cs	81 no data received
PERU	Jan 1 83	May 1 83	1 to 21	7	2	Bendix/Cs	Aug28 81
	May 1 83	Jun 1 83	1	7 to 8	2		

6. COMMUNICATIONS

The final phase of the upgrading of the SAO communications facility was completed during this reporting period. Both the NASCOM and the TWX/Telex hardware were upgraded to operate with eight level ASCII code and without paper tape. The final phase in this program was the upgrading of the Radio TTY link presently used to and from the laser tracking site in Arequipa, Peru. The backup minicomputer at Arequipa and the minicomputer in the SAO communications facility were both updated with new hardware (including modems) and software to allow computer-to-computer transfer of TTY traffic. When data are now received at SAO, they are transfered via computer link to the SAO VAX computer for editing, use in Quick-look orbits, and transfer to GSFC by NASCOM.

Voice and data links to and from Arequipa were operational during the reporting period, but due to the age of the radio equipment a number of outages requiring the use of a back-up transmitter were reported. We are experiencing some difficulty in obtaining spare parts.

Data links to and from the VAX computer were operational during the reporting period. Each of the three communications circuits (NASCOM, TWX/Telex, and Radio TTY) have separate circuits and ports to the VAX, allowing maximum flexibility in passing data.

Data from cooperating laser stations in Japan, Holland, Germany Switzerland, Austria, and England were handled via telex. Observation were routinely received from all other sites via the NASCOM line.

7. DATA SERVICES AND PROGRAMMING

The Data Services Group performs the central data processing necessary for the efficient operation of the SAO field stations. This group screens and validates all incoming data, generates orbital elements for all satellites being tracked by the SAO laser network and cooperating stations, supplies orbital elements to SAO stations and other agencies, and furnishes SAO laser data to the Crustal Dynamics Project at GSFC.

7.1 Data Services

The two major activities of Data Services are the quick-look processing cycle and final data processing. The quick-look activity cycles on a weekly schedule, in which the SAO and cooperating foreign field stations send small subsets of their acquired data through communications channels to Cambridge. These data then form the basis for generating updated orbital elements, which are communicated back to the field stations, where they are used to compute the look angles necessary for laser satellite ranging.

The full data sets on Linc magnetic tape are mailed from the field to Cambridge and sent through the final data-processing chain. This sequence of processes consists of an engineering filter to assess data quality, followed by a noise filter, a time correction program, and a formatter.

The quick-look functions of the Data Services operation have evolved into a stable, reliable, and smoothly-running procedure. Acquisition orbits were computed and transmitted each week virtually without incident. The quality of these orbits is very high; ephemerides are now routinely computed to the sub-10-meter level and, in the case of LAGEOS, to the 2-meter level.

In the first half of CY 1983, the Data Services group processed 44,673 laser quick-look data points and handled 1,125 passes of Starlette, BE-C, and LAGEOS from the SAO and cooperating stations (see Table 1).

During the reporting period, the Data Services group, using LAGEOS data from the SAO and NASA laser networks as well as from certain cooperating foreign organizations, provided 5-day mean pole positions as a by-product of the routine orbital determination and data assessment activity. The pole positions are transmitted weekly to the Bureau International de L'Heure (B.I.H.) in Paris as a rapid service to the world scientific community (see Figure 1).

In the first half of CY 1983, the Data Services group processed and sent 44,673 points on 1,125 passes of data to the Crustal Dynamics Project at GSFC. The Data Services group has maintained 60-day turnover on final data submission. Final data from the SAO laser network from April 1983 were transmitted to NASA by the end of this reporting period.

Figure 1

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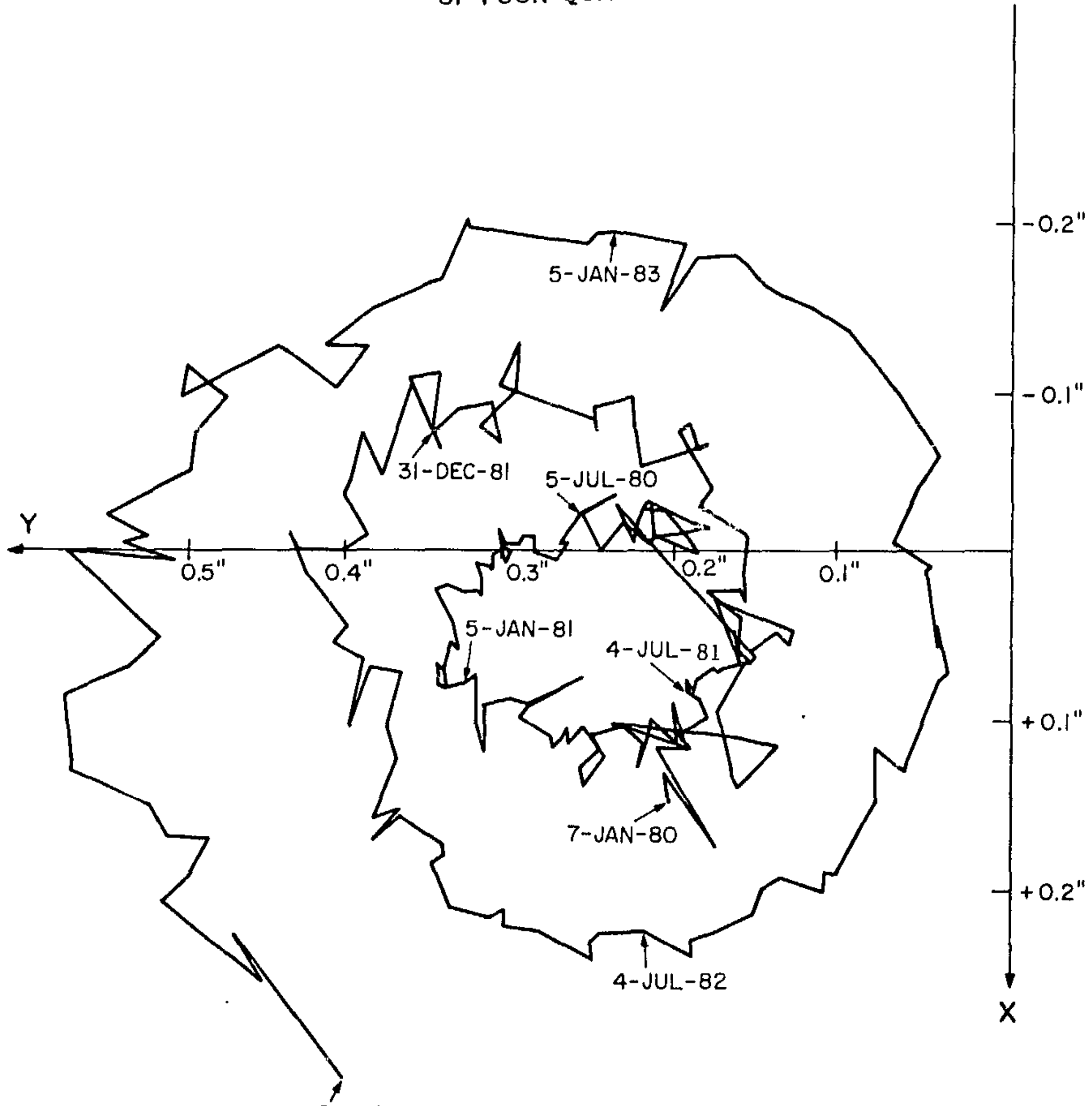


LAGEOS POLE POSITION (arcsec)
DERIVED FROM QUICK LOOK DATA
THREE AND ONE HALF YEARS

SAO compiles and publishes the quick-look data catalog for satellites tracked by the laser systems. The tabulation includes all quick-look data submitted. This catalog also now contains the 5 day mean positions of the earth's pole which is obtained as a by-product of the data validation process.

The quick-look catalog for CY 1982 is being prepared for distribution.

7.2 Programming Support

SAO maintains a small staff of computer programmers who support the operation of its tracking program. In addition to routine maintenance and upgrading of the minicomputer and production processing programs, the Programming Group develops software to meet new needs and supports the Data Services Group in routine processing as necessary. The Programming Group analyzes test data for laser-system maintenance and for planning laser-system modifications to improve performance.

7.2.1 Final Updates to the Field Software

In January, the version of Direct Connect with operator controllable mode sequencing and provisions for operating with a disabled digitizer was verified and placed in service at Arequipa. A second, revised version was installed the following month. After field use, additional changes were requested by the field personnel. These final updates were completed in June, with final debugging in progress at the end of this reporting period. It is anticipated that this program will be frozen in July or August.

7.2.2 IRV Testing

IRV generation software was tested in March with the Maui laser site, demonstating that SAO IRVs were suitable for acquiring LAGEOS and Starlette. A simulation of a weekly prediction environment was begun and continued throughtout the remainder of the reporting period to gain experience in anticipation of a production mode of operation. A series of utility programs was prepared in April to assist in the data processing of IRVs. In May IRVs for BE-C were successfully tested at Maui.

7.2.3 Orbit Routines

Dr. D. Lelgemann of the Institut fur Angewandte Geodasie, West Germany, visited SAO for a week's discussion of upgrading the ephemeris package at the Wettzell site. A package of lunar and solar perturbation routines and supporting utility routines was prepared and shipped to Germany. We were subsequently notified that Wettzell had noticed an improvement in predictions.

In March and April the SAO Differential Orbital Improvement program, GRIPE, was recompiled under DEC's VAX VMS version 3.1 to (1) take advantage of improvements in mathematical library routines and, (2) consolidate several slightly different versions into one unique, properly documented version. We also took time to do some cleaning up, including removal of vestiges of obsolete CDC 6400 system calls.

7.2.4 NOVA Nine-Track Software

In January, the DG NOVA program to drive 9-track magnetic tape was completed and in February the VAX program CEL50 was modified to read from 9-track tape instead of 7-track tape. The modification was also made to the INVENTORY program. These programs are the entry points into the VAX-oriented data processing system of reduced and raw laser data. The introduction of the 9-track drives allowed processing to completely bypass the 7-track tape system (which is another vestige of the CDC-6400 used at the Observatory until 1979).

In April, NOVA Data channel techniques were incorporated into the utility program used to access raw laser data which has been archived on 9-track magnetic tape. Completion of this routine gives us a set of data manipulation packages permitting interchange between linc tape and 9-track tape. These packages were made operational in June.

7.2.5 Communications Software

In May, the Observatory Computer Center upgraded terminal port hardware; an unexpected side effect of this change was the generation of a problem with VAX to NOVA file transfer and terminal emulation software. This program (run on the mini-computer) was upgraded so that it could tolerate a much broader variation in response time from the VAX. Unfortunately, work on this program was prolonged by a subtle hardware problem which was only in evidence in this routine. By June, both hardware and software were repaired and operational.

8. CONFIGURATION CONTROL

In FY 1982, the Crustal Dynamics Project established a Satellite Laser Ranging Configuration Control Board (CCB) to review and approve all system hardware, software, and procedures changes that would effect data quality and quantity. As a part of its function, the board organized a panel under the chairmanship of Dr. Michael R. Pearlman to develop a laser system characterization model that could be used as a standard to specify measurement and system performance. SAO developed a draft document and circulated it to panel members and other workers and data users in the satellite ranging community. The latest version of the document including review comments and suggestions is included in Appendix 3. A recommendation has been made to the CCB that the model now be incorporated into the project procedures.

9. DATA QUALITY

The ranging performance capability of the laser in Arequipa is assessed by examination of both systematic errors and range noise. These refer to performance of the ranging machine itself, leaving aside issues such as atmospheric correction, spacecraft center of mass correction, and epoch timing for discussion elsewhere.

9.1 Range Accuracy

The systematic errors of the laser system have been divided into three categories: spatial, temporal, and signal-strength variations (see Pearlman 1981). Spatial variations refer to differences in time of flight depending on the position of the target within the laser beam. Temporal variations relate to system drift between pre-pass calibration and post-pass calibration. Variations in range due to changes in signal strength from pulse to pulse are a function of receiver characteristics.

Spatial Variations

Spatial variations, or the wavefront error, which arise from the multimode operation of the ruby lasers, have been measured at Arequipa using a distant target retroreflector to probe the beam. Figure 2 shows the results for different ruby doping levels. The wavefront measurements on May 11 using the .03% Cr doped ruby rod show an r.m.s. variation across the wavefront of 1.4 cm and peak-to-peak variations of 4.5 and 5.0 cm. It appears, however, that a large component of this variation is the

temporal stability or measurement reproducibility as evidenced by the averaging of measurements at the beam center. The results on June 4 using the .05% CR doped ruby are a little worse, showing r.m.s. wavefront distortion of 1.3 cm and 2.0 cm and peak-to-peak variations were of 5.3 cm and 6.9 cm. Once again, a significant component of the wavefront distortion measurement appears to be temporal variation, indicating that these wavefront measurements are probably giving an over estimation of wavefront distortion.

Figure 2.

WAVEFRONT MEASUREMENT AREQUIPA LASER									
DATE	TIME	SPACING BETWEEN POINTS (ARC MIN)	RUBY ROD DOPING	PRF (PER MIN)	AVERAGE* NUMBER OF PHOTOELECTRONS RECEIVED PER PULSE	TEMPORAL STABILITY AT BEAM CENTER		WAVEFRONT DISTORTION	
						RMS (CM)	MAXIMUM EXCURSION (CM)	RMS (CM)	MAXIMUM EXCURSION (CM)
MAY 11 1982	03 HRS	.42	.03%	20	30	1.8	4.1	1.4	5.0
	05 HRS	.42		20	28	1.4	3.3	1.4	4.5
JUNE 4 1982	03 HRS	.42	.05%	20	28	1.5	3.2	2.0	6.9
	06 HRS	.42		30	28	1.5	3.0	1.3	5.3

*FIFTY PULSES AT EACH OF TWENTY POSITIONS

The difference between the .03% and .05% doping may not be statistically significant; but the lower doping probably allowed more uniform pumping which may have given a more uniform wave front (mode pattern).

Temporal Variations

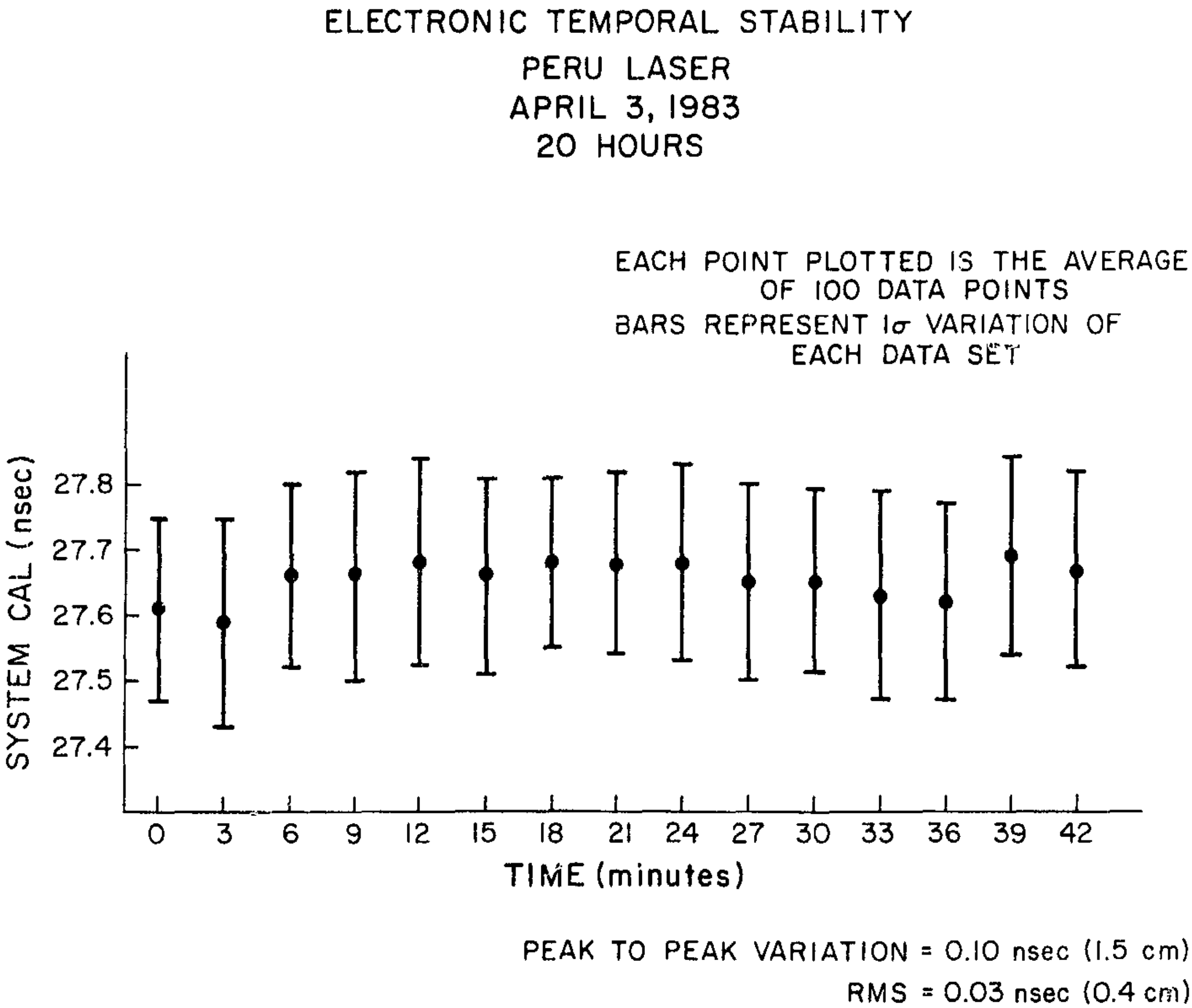
The temporal variations or system drift are estimated through electronic and ranging calibrations.

Electronic calibrations using a 3 nsec pulse through a fixed delay line to start and stop the ranging system were used at Arequipa during the previous reporting period to estimate the stability of the electronics. An example of the results over a period of 45 minutes (similar to the length of a satellite pass) is shown in Figure 3. The r.m.s. variation of the means is less than 1 cm with peak-to-peak values of less than 2 cm. A second example taken over a period of 24 hours is shown in Figure 4. In this case, the r.m.s. variations of the set means is 1 cm with the peak-to-peak variation equal to 4 cm. The larger variations in this latter case are probably due in large part to the diurnal fluctuations in line voltage experienced at Arequipa.

Temporal stability of the full system was measured with the billboard target. Results for ranging over a period commensurate with a Lageos pass (90 minutes) are shown in Figure 5. The r.m.s. variation of the set means is 1.2 cm while the peak-to-peak variation is 4.6 cm, which is slightly higher than the electronics tests.

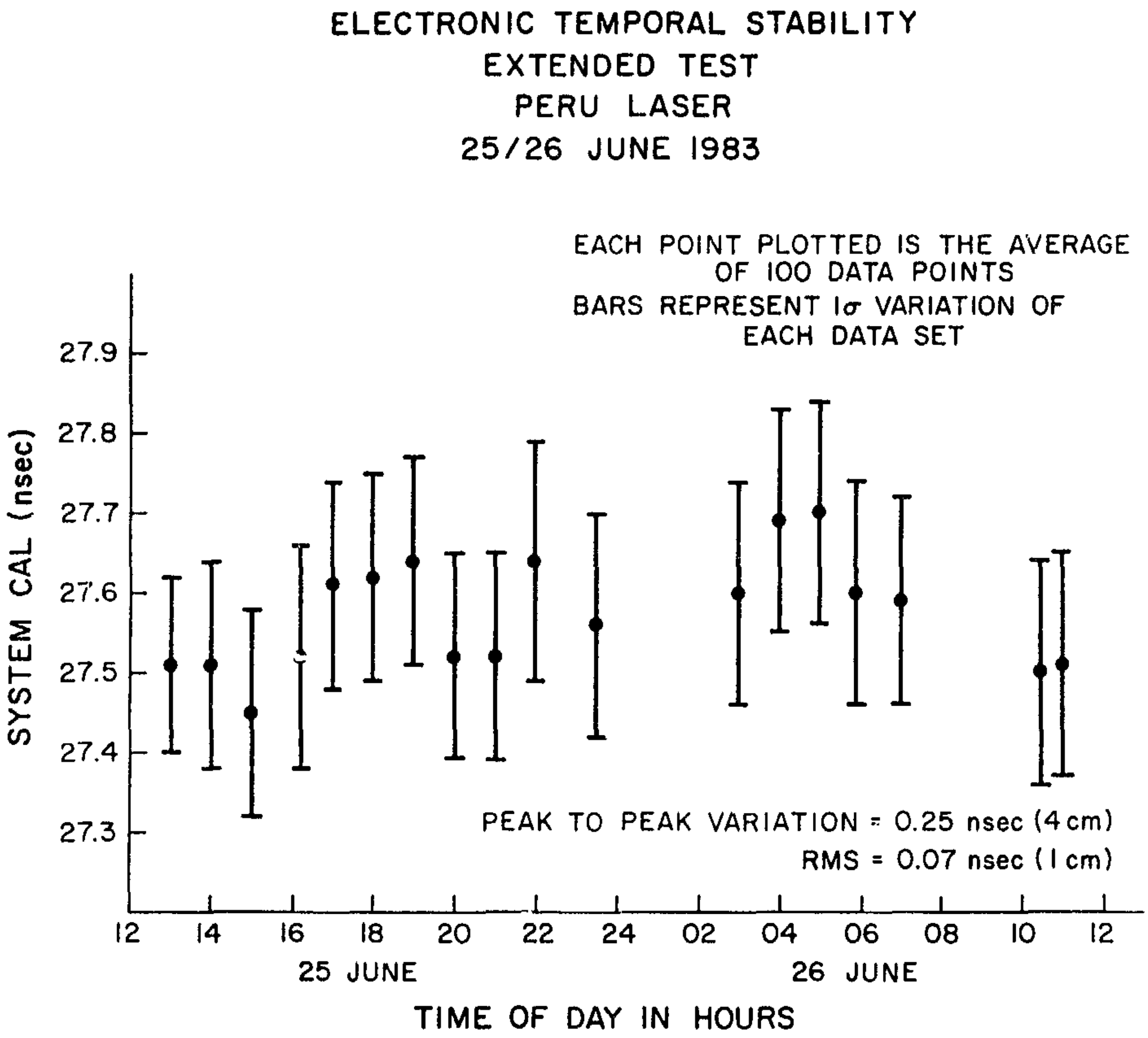
Temporal stability is also estimated by the difference between pre-pass and post-pass calibrations to the billboard target. These measurements are taken at about 5 photoelectrons with 50-100 calibration points in each calibration. Results for the months of May and June 1983, shown in Figures 6 and 7, show an r.m.s. variation in pre-calibration minus post-calibration differences of about 2.5 cm.

Figure 3.



ELECTRONIC TEMPORAL STABILITY
PERU LASER
APRIL 3, 1983
20 HOURS
EACH POINT PLOTTED IS THE AVERAGE OF 100 DATA POINTS
BARS REPRESENT 1σ VARIATION OF EACH DATA SET
SYSTEM CAL (nsec)
27.8
27.7
27.6
27.5
27.4
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
TIME (minutes)
PEAK TO PEAK VARIATION = 0.10 nsec (1.5 cm)
RMS = 0.03 nsec (0.4 cm)

Figure 4.



ELECTRONIC TEMPORAL STABILITY
EXTENDED TEST
PERU LASER
25/26 JUNE 1983
EACH POINT PLOTTED IS THE AVERAGE OF 100 DATA POINTS
BARS REPRESENT 1σ VARIATION OF EACH DATA SET
SYSTEM CAL (nsec)
27.9
27.8
27.7
27.6
27.5
27.4
27.3
PEAK TO PEAK VARIATION = 0.25 nsec (4 cm)
RMS = 0.07 nsec (1 cm)
12
14
16
18
20
22
24
02
04
06
08
10
12
25 JUNE
26 JUNE
TIME OF DAY IN HOURS

Figure 5.

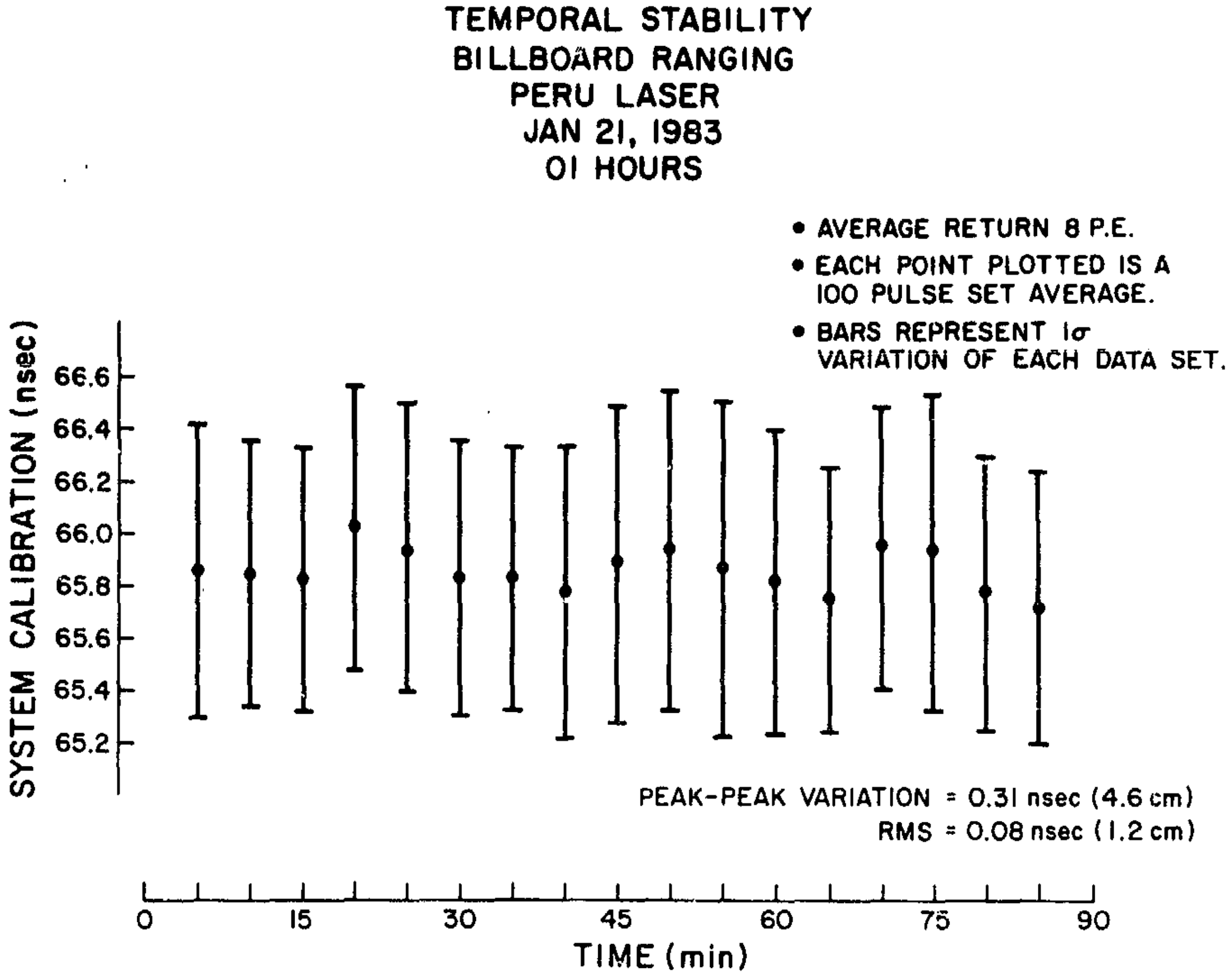

TEMPORAL STABILITY
BILLBOARD RANGING
PERU LASER
JAN 21, 1983
01 HOURS
• AVERAGE RETURN 8 P.E.
• EACH POINT PLOTTED IS A 100 PULSE SET AVERAGE.
• BARS REPRESENT 1σ VARIATION OF EACH DATA SET.
SYSTEM CALIBRATION (nsec)
66.6
66.4
66.2
66.0
65.8
65.6
65.4
65.2
PEAK-PEAK VARIATION = 0.31 nsec (4.6 cm)
RMS = 0.08 nsec (1.2 cm)
0
15
30
45
60
75
90
TIME (min)

Figure 6.

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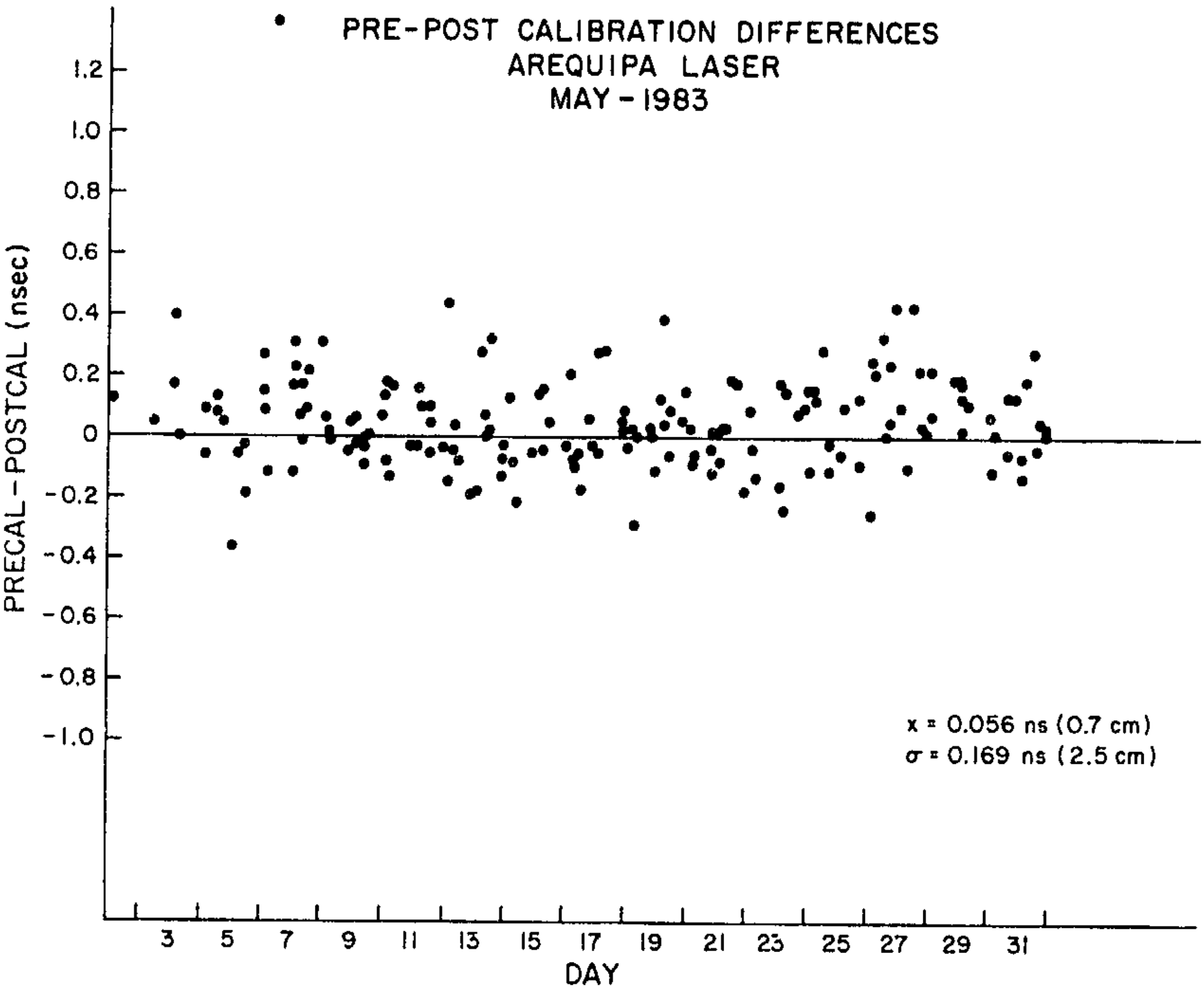
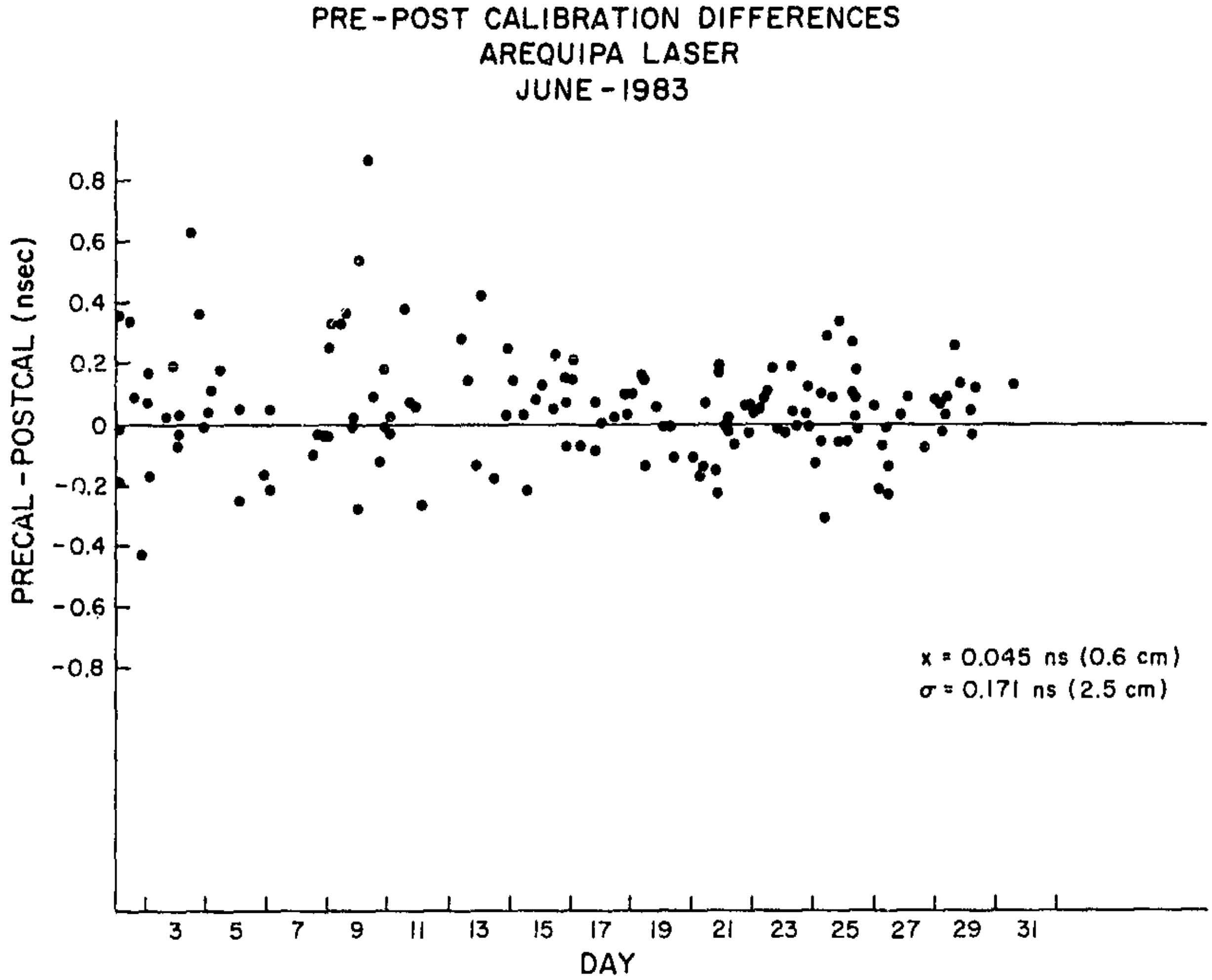


Figure 7.


PRE-POST CALIBRATION DIFFERENCES
AREQUIPA LASER
JUNE-1983
PRECAL-POSTCAL (nsec)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
x = 0.045 ns (0.6 cm)
σ = 0.171 ns (2.5 cm)
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
DAY

Signal Strength

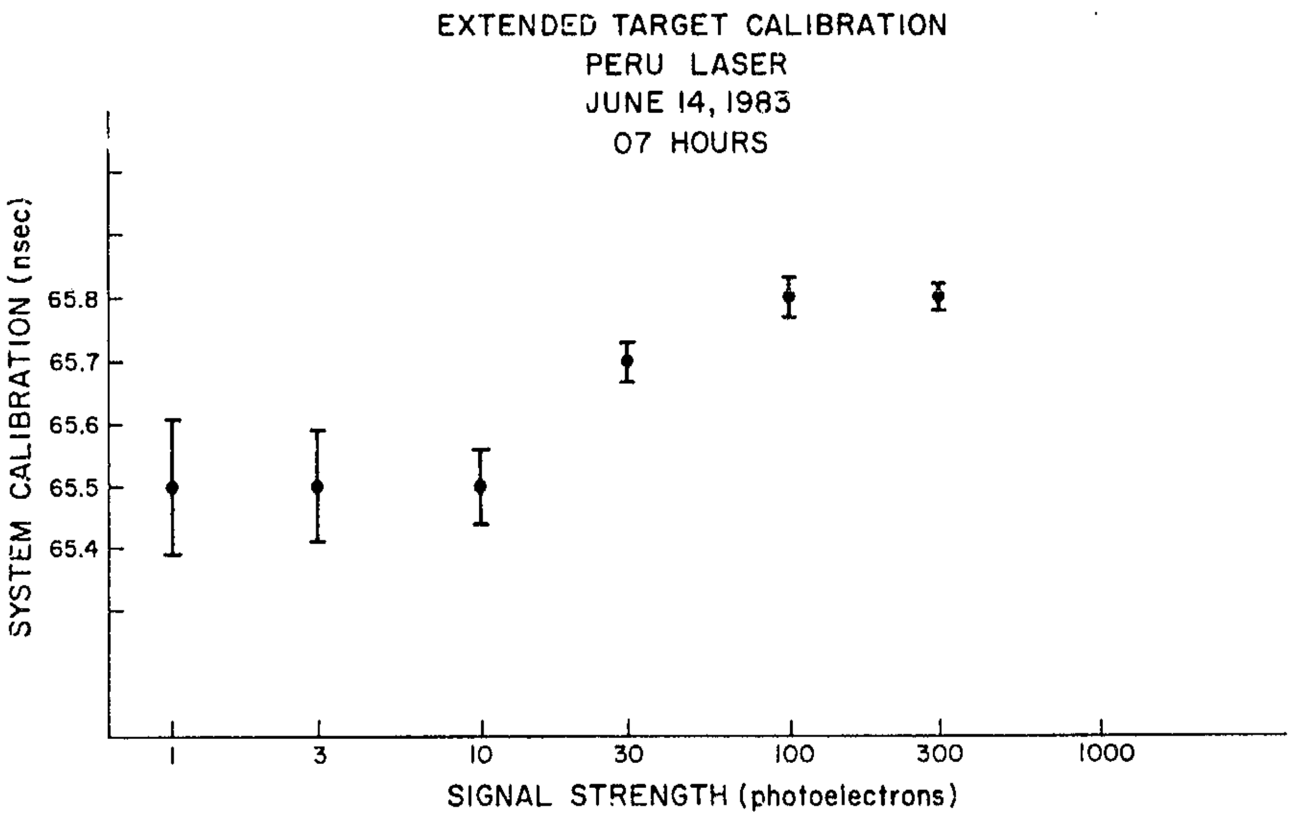
The SAO lasers operate at the single photoelectron level on Lageos and in the range of 1-50 photoelectrons on low orbiting satellites. Variations in apparent range with signal strength have been examined with extended target calibrations over the dynamic range of the laser instrument (See Figure 8). The mean calibration over the operating range of 1-50 photoelectrons is typically flat to ± 0.15 nsec (2.2 cm) with maximum peak-to-peak excursion of 0.3 nsec (4.5 cm). We believe that the lowering trend at lower signal strengths is due to non-optimization of the matched filter. The matched filter was optimized for nearly symmetrical laser output pulse, whereas the single photoelectron pulses tend to be somewhat asymmetric.

Low orbiting satellites are tracked over the full dynamics range in signal strength, and accordingly the above variations should be good estimates of the systematic range biases due to this effect. In the case of LAGEOS, where calibration and ranging are done in the region of 10 p.e. or less, the systematic effects due to variations in signal strength are probably less.

A summary of the range error components is tabulated in Figure 9. Assuming that these errors are independent, the root-sum square (rss) error due to the r.m.s. systematic sources is about 4 cm. We use this value to characterize the systematic errors that can be expected for data averaged over a pass.

The long term stability of the system is shown in the history of calibration data taken over a period of a month. Figures 10 and 11 show the results for May and June 1983. The data during May (Figure 10) show distinctly the times when laser system service was performed (May 4, May 8 and May 22). The results in June also show the results of servicing early in the month. During June there also appears to be a slight secular trend in the data probably due to equipment aging.

Figure 8



EXTENDED TARGET CALIBRATION
PERU LASER
JUNE 14, 1983
07 HOURS
SYSTEM CALIBRATION (nsec)
65.8
65.7
65.6
65.5
65.4
1
3
10
30
100
300
1000
SIGNAL STRENGTH (photoelectrons)

Figure 9

SAO LASER NETWORK

SYSTEMATIC ERROR SUMMARY

SOURCE	EST. ERROR (RMS)	EST. ERROR (PEAK)
Wavefront (Spatial)	2.0 cm	5.0 cm
System Drift (Temporal)	2.5 cm	6.0 cm
Calibration (Signal Strength)	2.2 cm	4.5 cm
	--------	--------
R.S.S.	3.9 cm	9.0 cm

Figure 10

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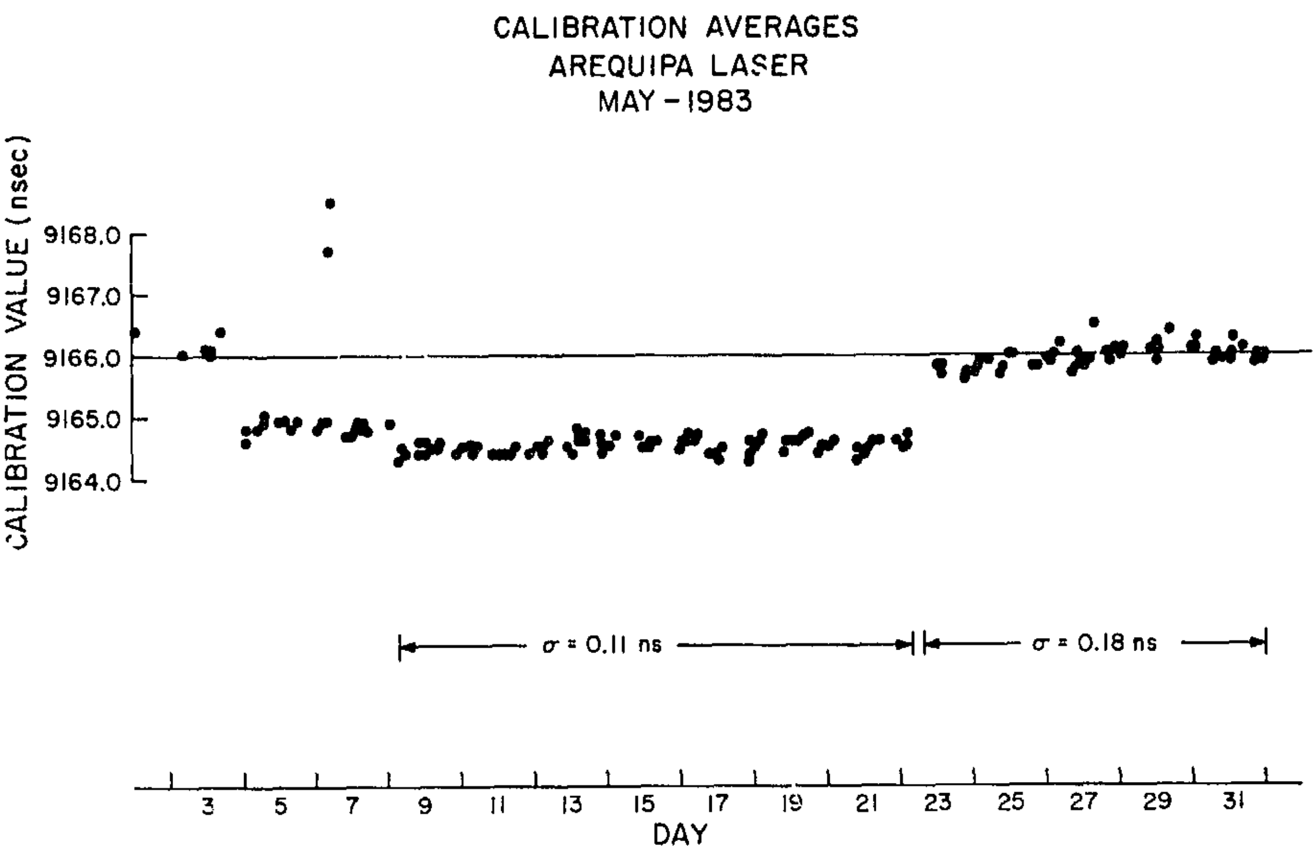

Figure 11

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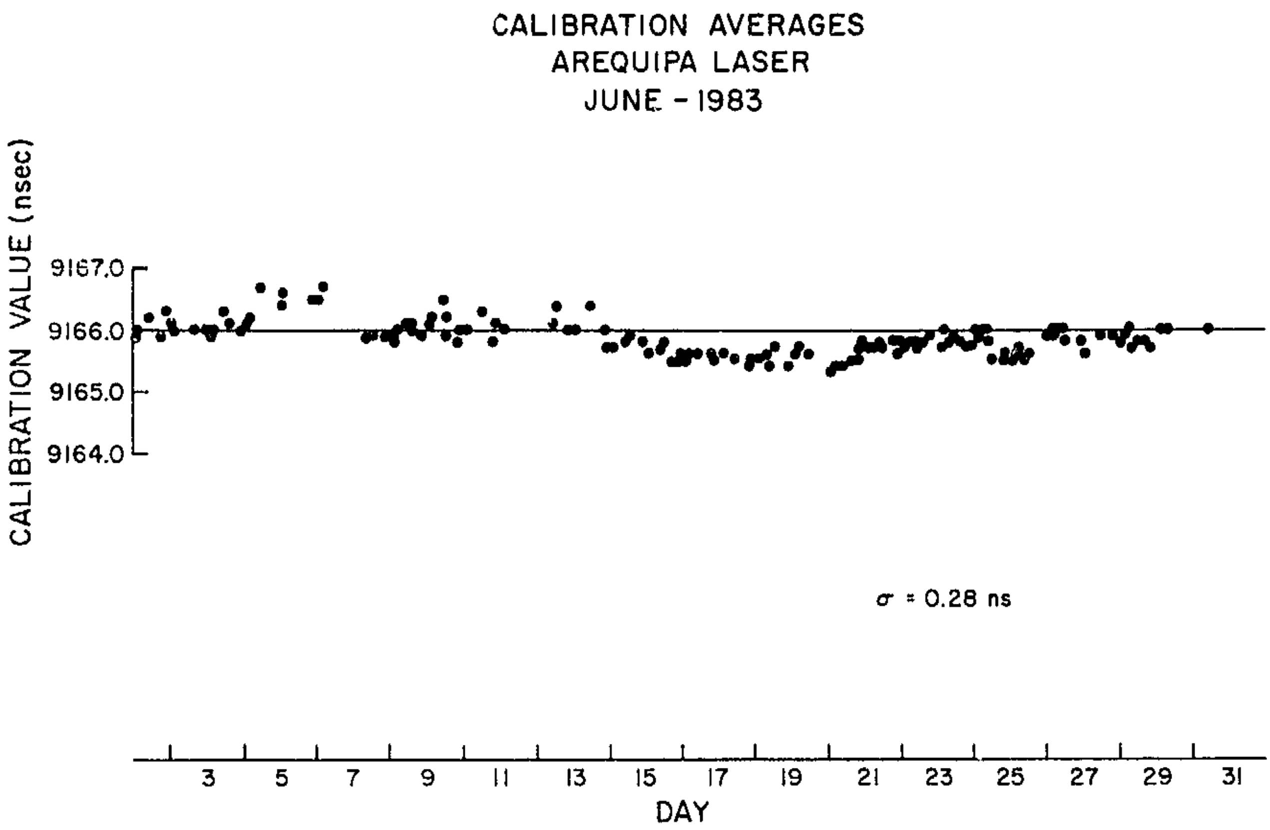

9.2 System Noise

The noise performance of the system was measured during the previous reporting period by examining range noise (1 σ) verses signal strength in calibration runs on the billboard target. This has the advantage of highlighting system jitter by averaging out effects of wavefront distortion. The results of several calibration sequences are shown in Figure 12, along with the theoretical results for a 3 nsec gaussian pulse for reference. At low and intermediate signal strengths, the range noise follows closely the anticipated $n^{-1/2}$ dependence and is consistent with a pulse of about 3 nsec width. At high signal strengths, the system noise levels off at about 0.2 nsec (3 cm) which is probably dominated by the jitter in the P.M.T.

The distribution of range residuals (1σ) on a per pass basis for Lageos, Starlette, and BE-C at Arequipa during this reporting period are shown in Figures 13, 14 and 15. Range noise on Lageos varies typically from 13-18 cm as would be anticipated for 1-2 photoelectron events with a 3.0 nsec wide pulse. There is probably some corruption due to the jitter in the electronics and the PMT.

Figure 12

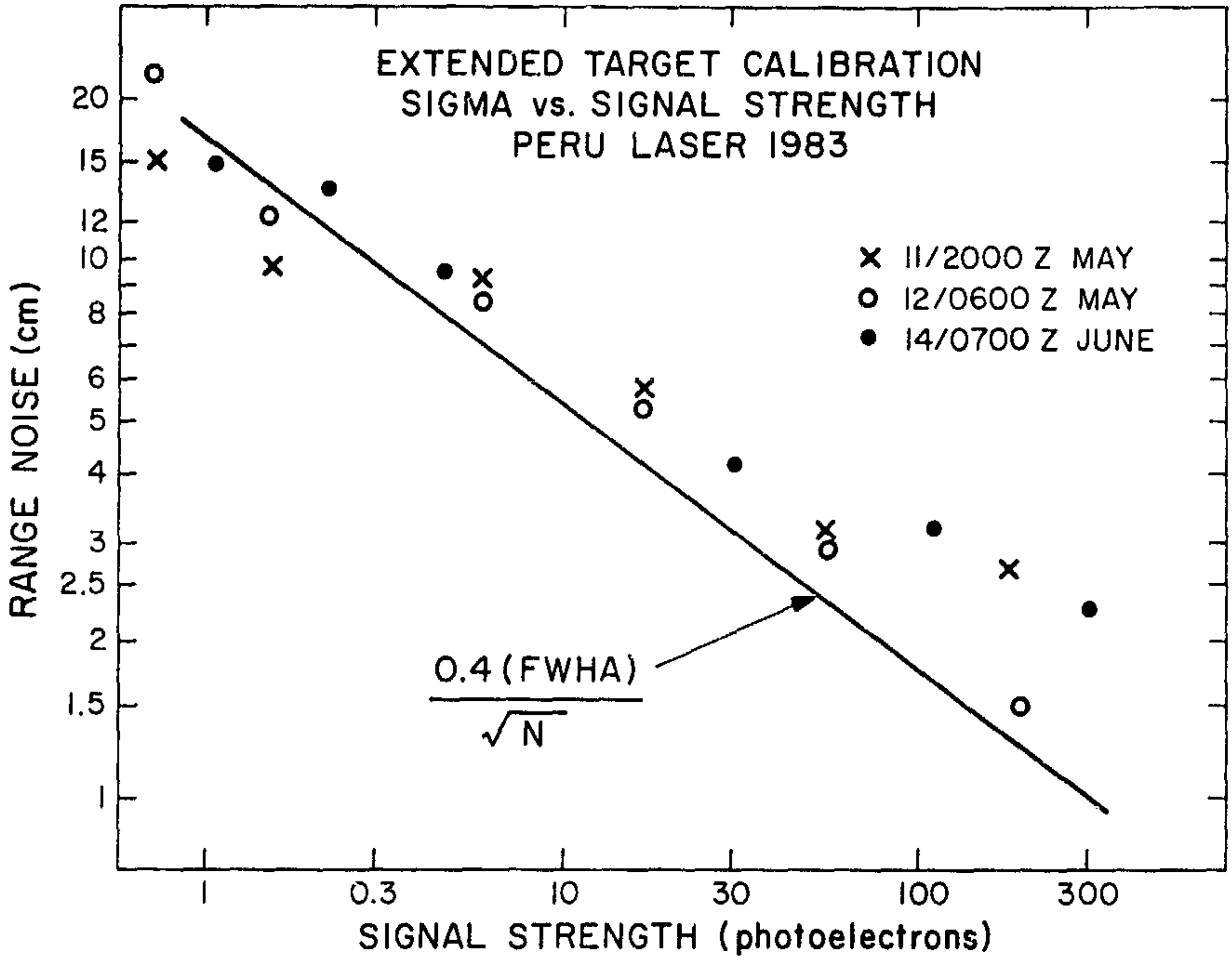
EXTENDED TARGET CALIBRATION
SIGMA vs. SIGNAL STRENGTH
PERU LASER 1983
× 11/2000 Z MAY
o 12/0600 Z MAY
• 14/0700 Z JUNE
0.4 (FWHA) / √N
RANGE NOISE (cm)
20
15
12
10
8
6
5
4
3
2.5
2
1.5
1
SIGNAL STRENGTH (photoelectrons)
1
0.3
10
30
100
300

Figure 13

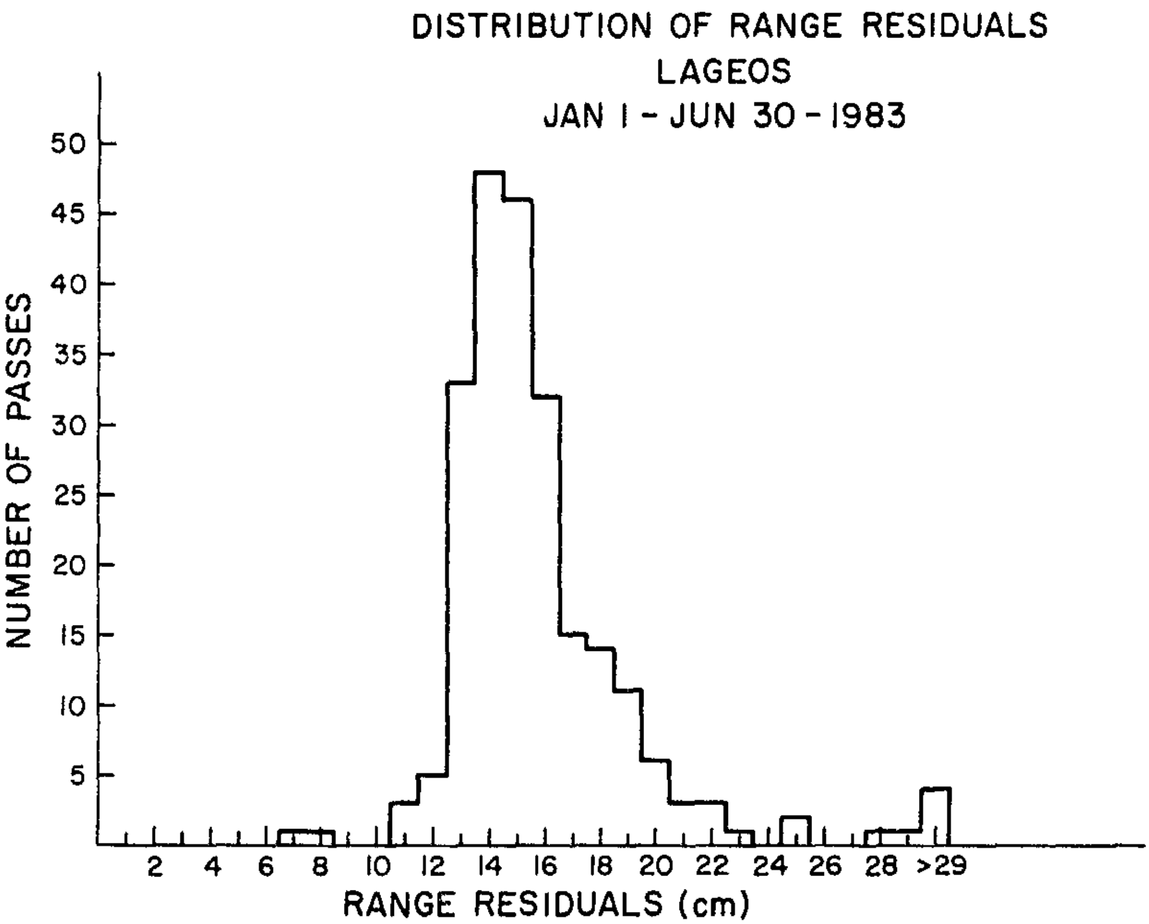
DISTRIBUTION OF RANGE RESIDUALS
LAGEOS
JAN 1 - JUN 30 - 1983
NUMBER OF PASSES
50
45
40
35
30
25
20
15
10
5
2
4
6
8
10
12
14
16
18
20
22
24
26
28
>29
RANGE RESIDUALS (cm)

Figure 14

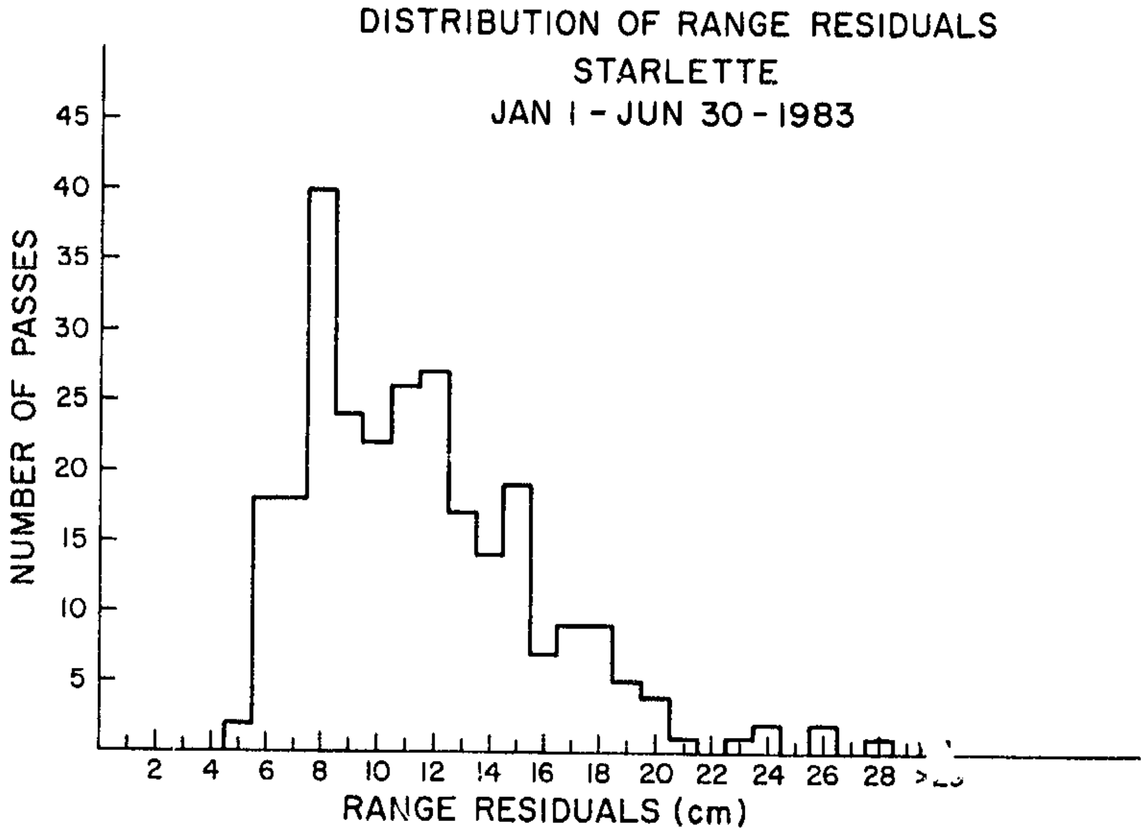
DISTRIBUTION OF RANGE RESIDUALS
STARLETTE
JAN 1 - JUN 30 - 1983
NUMBER OF PASSES
45
40
35
30
25
20
15
10
5
2 4 6 8 10 12 14 16 18 20 22 24 26 28
RANGE RESIDUALS (cm)

Figure 15

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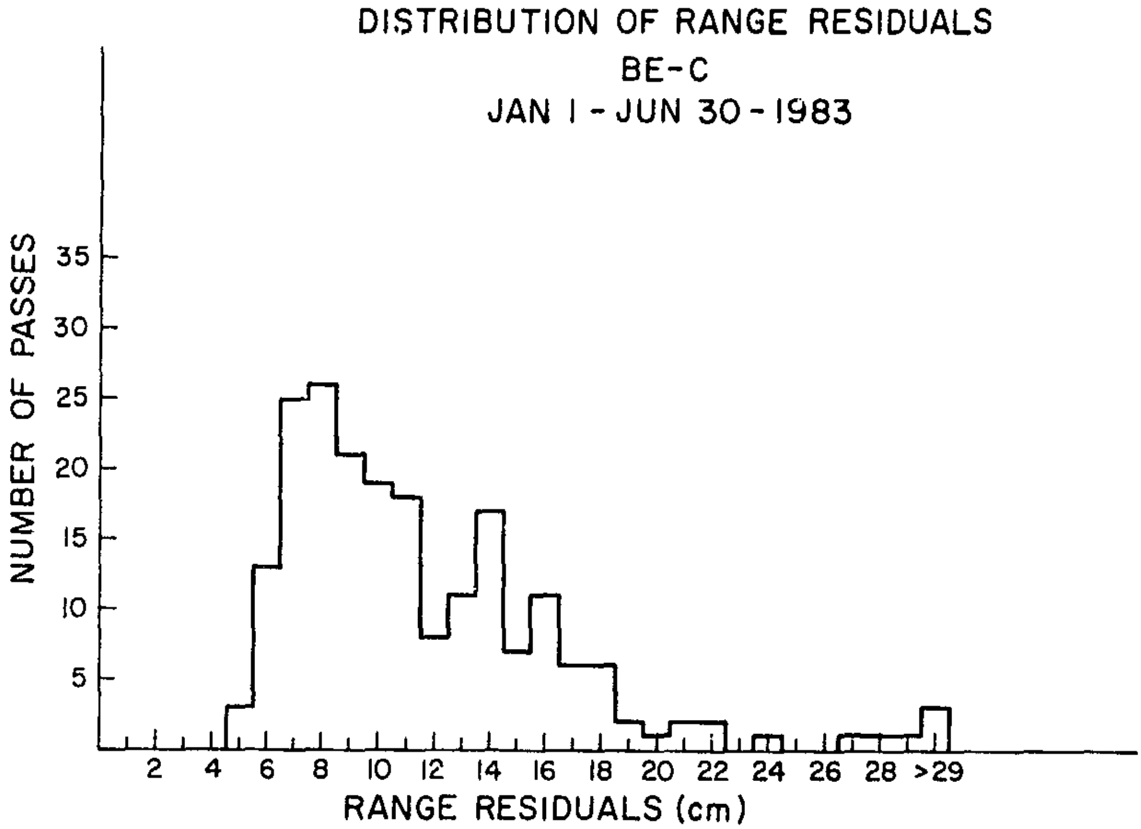


On the lower satellites, return signal strengths are typically 5-30 photoelectrons. Short arc fits to quick-look data give r.m.s. values of 6-18 cm. At the higher signal strengths, the range jitter in the PMT and the electronics becomes significant and tends to degrade the $n^{-1/2}$ noise dependence.

10. RELOCATION OF SAO 1 TO MATERA, ITALY

In 1982, NASA, SAO and representatives of the Italian National Space Council (a part of the Consiglio Nazionale delle Ricerche (CNR)) agreed on the relocation of SAO 1 to Italy. Under the agreement reached, the laser was to be relocated to a mutually-agreed upon site at CNR expense; CNR would then take responsibility for operations. SAO would provide headquarters support, configuration control, and network integration and coordination.

Based on weather data, seismology, logistics and support considerations, and geographic location, a site about 10 miles west of Matera was selected. A building design was submitted to SAO by the CNR in June 1982. The design was approved with minor modification in July 1982, and construction was underway in early FY 1983. A milestone chart for the relocation activity is shown in Figure 16.

Three Italian technicians visited SAO headquarters for two weeks in February for intensive classroom and laboratory training. Two other technicians from Italy spent two weeks at the Arequipa site for hands-on training in laser tracking.

An agreement between SAO and CNR for the set-up and operation of the satellite ranging system was signed in March. A copy is included in Appendix 4.

Two SAO engineers arrived at Matera at the end of March to set-up the equipment and train the Italian personnel. A full crew from Telespazio, the Italian contractor who will operate the Matera site, was available on-site to participate in this activity.

The bulk of the laser station equipment arrived via sea freight at Matera in March with an air shipment of the second station mini-computer arriving in May. Some damage was sustained by the system during shipping and storage. In particular, the cooling unit required major repair by a local shop.

The service building was completed in mid-March, providing an on-site area for unpacking and preliminary examination and check-out. The laser building was completed in stages; it was available for occupancy in May, with the roof completed in late June. Some problems arose with the height of the roof, which had to be raised after initial installation.

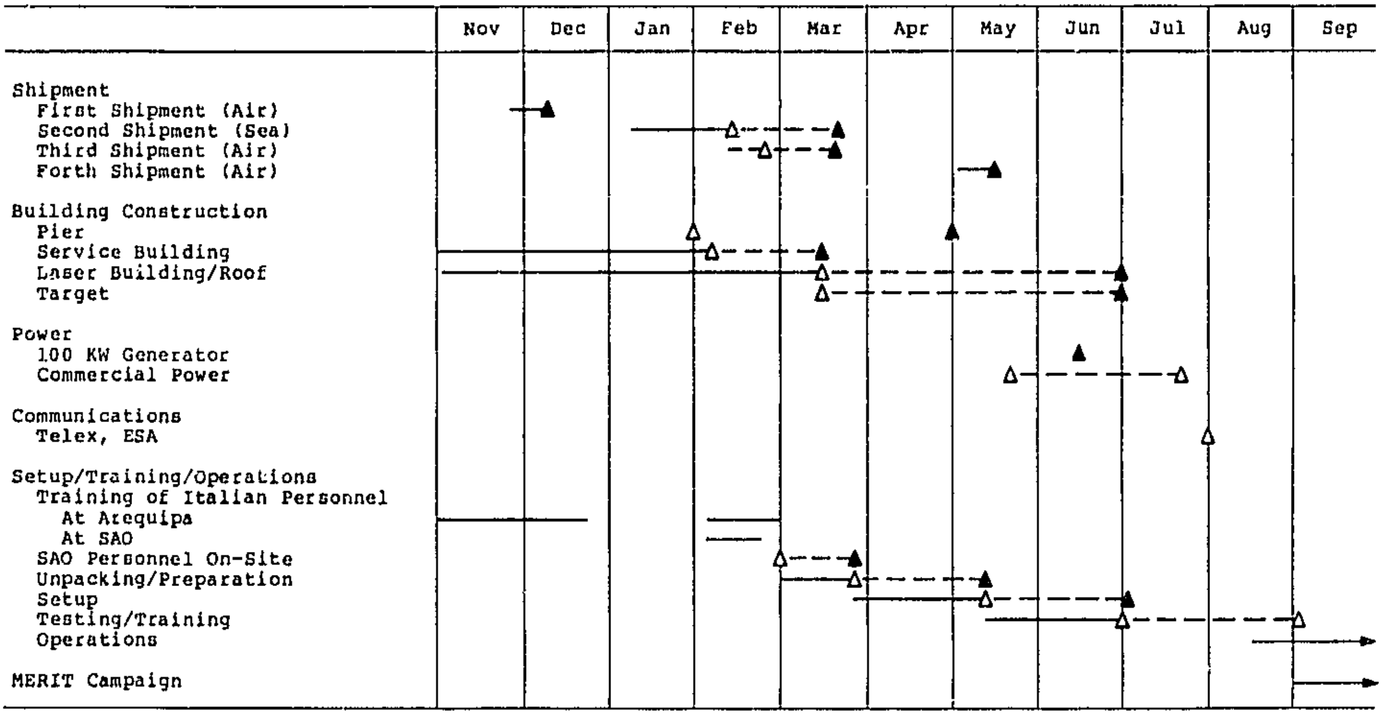
In June, the site was provided with a 100 KW generator to furnish power until commercial service becomes available this summer. The schedule is running about 4-6 weeks late due mainly to slips in the completion of facilities, and equipment damage sustained during shipment and storage. The Italians have worked very hard in an attempt to reclaim some of the lost time, and some makeshift provisions allowed us to get underway before the facilities were complete.

As of the end of this reporting period, all of the electronic chassis had been checked out and were in place, with system integration underway. The components in the photoreceiver, mount, and laser had been cleaned and

assembled. We anticipate that the station will be operating by early August and that one SAO engineer will remain on-site for several additional months to continue instruction and technical assistance.

Figure 16

Schedule for Matera Installation



11. STATUS OF SAO 3 AND 4

11.1 SAO-3

Serious discussions are underway with Tel Aviv University and the new Israeli Space Agency on the relocation of SAO-3 to a site in southern Israel. The basis being sought for such a relocation is similar to that arranged with the CNR in Italy: SAO/NASA would: furnish a refurbished laser for operation by a local agency as part of the International Cooperating Network; support setup and training; and provide headquarters support. Although discussions are still in a preliminary stage, an FY 1984 installation seems quite practicable.

The SAO-3 laser system has been returned to SAO from Orroral Valley for upgrading which is now underway. All of the upgrading will be completed by late July except for the following:

1. Paper tape reader and punch.
   Refurbishment awaits the arrival of parts due in August; a 50 Hz conversion kit is also to be included.

2. Linc tape drives.
   Refurbishment awaits the arrival of new tape heads due in August.

3. Laser (Goniometer) Readout Optics
   All available optical components are now with the setup team in Matera. Once installation there is complete, the remaining components will be returned to SAO-3. In all likelihood, it will be necessary to

purchase, refurbish, and/or fabricate some of the optical components.

4. Minicomputer.

One minicomputer for SAO-3 is available in Cambridge now. In addition, as with Arequipa and Matera, SAO plans to provide a second system for off-line processing and as a spare. Several machines with significant amounts of hardware have been acquired by SAO under surplus and are due to arrive in early July. After an examination of the equipment, a decision on any additional requirements will be made. However, with the newly acquired system and parts already available at SAO, it is unlikely that any major items will have to be purchased.

11.2 SAO-4

During the last reporting period, the system electronics and minicomputer from the Mt. Hopkins laser (SAO-4) were returned to Cambridge and set up as a laboratory and diagnostic test facility. Many of the optical and electronic components from the station are being used to outfit and provide spares for SAO-1 and SAO-3. The rest of the equipment including the laser, the photoreceiver, and the mount will remain in storage at Mt. Hopkins.

12. PERSONNEL

12.1 TRAVEL

Dr. Michael R. Pearlman travelled to Goddard Space Flight Center in January to attend the Crustal Dynamics Quarterly Review Meeting. In June, he again travelled to Goddard for the TLRS Design Review meeting and for discussions with the Crustal Dynamics Project Personnel.

Ms. Margaret Warner, Project Administrator for the Satellite Tracking Program, travelled to the Smithsonian Institution in Washington in March to confer with officials there on programs funded by Excess Currency (PL-480 funds).

On May 19, Messrs. Noel Lanham and James Maddox attended the Laser System Engineering Meeting at Goddard Space Flight Center.

On June 24, Margaret Warner, while in the area for other purposes, visited RCA Service Company headquarters in Cherry Hill, N.J. for discussions with administrative and budgetary personnel. No Grant funds were expended in support of this trip.

12.2 VISITORS

In January, Dr. Franco Palutan and Messrs. Sacchini, DelRosso, and Cenci, all personnel from Telespazio, the firm contracted by CNR to operate the Matera laser station, visited SAO for training by headquarters staff on station operations, hardware and software orientation and techniques.

Dr. Dieter Lelgemann, of the Institut fur Angewandte Geodasie in Frankfurt, West Germany, visited SAO in January to work with the Data Services and Programming group to familiarize himself with the upgrades to the field prediction program which have occurred over the last two years. His visit resulted in a transfer of some two dozen computer files and test data which were used to improve the prediction capability at Wettzell.

Six members of the North China Research Institute of Electro-Optics visited SAO headquarters for a few days in April to hold technical discussions on laser ranging systems. Xing Zhongjun, Li Ru Wang, Wan Baorong, Wang Ying Ru, Liu Xianjun, and Zhou Hou Wen met with Dr. Michael Pearlman and various technical staff while here.

Mr. Yahuda Bock, who was visiting Massachusetts Institute of Technology and the Air Force Geophysics Laboratory on a fellowship program from Israel, has met with Dr. Michael Pearlman several times to discuss the possibility of relocating the SAO-3 laser to a site in southern Israel in cooperation with Tel Aviv University. Also present for one of the discussions was Mr. Giora Tzur, Consul for Scientific and Economic Affairs, Consulate General of Israel.

Mr. Dana Seaman, former Natal, Brazil station manager, visited headquarters for a day to discuss a possible field position if SAO is the winning bidder of the contract for Goddard Laser Tracking Network mission support.

12.3 PERSONNEL

Messrs. Jakob Wohn and Donald Patterson, both SAO engineers, travelled to the site of the new laser station in Matera, Italy during the last week in March to oversee the setup of the laser station and operations there. It is expected that they will stay in Italy thru July. All travel and local subsistence expenses for Messrs. Wohn and Patterson are borne by the CNR.

Mr. David Hallenbeck, manager of the Arequipa, Peru station, was at headquarters for a week during his home leave in March.

REFERENCES

1981 Current Status and Upgrading of the SAO Laser Ranging Systems (M. Pearlman, N. Lanham, J. Wohn and J. Thorp). Presented at the Fourth International Workshop on Laser Ranging Instrumentation, Session I, in Austin, Texas, October.

Appendix 1

DEVELOPMENT OF IMPROVED
MODELS OF THE THERMOSPHERE AND EXOSPHERE

Quarterly Progress Report Nos. 6, 7, and 8

For the period 1 July 1982 through 31 March 1983

Contract F19628-81-K-0033

Principal Investigator

Mr. Jack W. Slowey

May 1983

This report is intended only for the
Internal Management use of the Contractor and the Air Force

Prepared for

Air Force Geophysics Laboratory
Hanscom Air Force Base, Massachusetts 02731

Prepared by

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

APPENDIX 1 REMOVED BY DOCUMENT EVALUATOR BECAUSE OF LIMITATION - FEB. 14, 1984

Appendix 2

SUMMARY

Time related characteristics of the Amperex XP2233B photomultiplier tube were measured.

The single photoelectron transit time jitter of an apertured PMT at an overall bias voltage of 2200V was measured to be 0.4 nsec with a 100 picosecond wide light source.

The optimum size aperture for this 44 mm diameter tube was determined to be 24 mm in diameter.

The 0.4 nsec SPE jitter implies a ranging system will not be PMT limited till the source pulse width is about 1.5 nsec. This was verified.

Various tube operating parameters were changed in an attempt to reduce the SPE transit time jitter further without success.

Amperex has introduced a new faster PMT (PM2254B) into production. This tube is physically and electrically compatible with the XP2233B (a minor wiring change to the PMT socket would be required). According to the Amperex specifications, this new tube will reduce the single electron transit time jitter to 0.25 nsec.

INTRO

In the upgraded SAO Laser Ranging System, we are using an Amperex XP2233B Photomultiplier tube as the photodetector with an EMI Gencom base designed for this PMT. This tube and base were selected as a low cost compromise between (1) fast risetime and good pulse reproduction, and (2) reliability and tolerance for high background noise. The PMT and base were then laboratory tuned for minimum distortion with short duration low-level input pulses. The system worked well in field testing at Mt. Hopkins and in the year since it was installed in the Peru field station.

The original laboratory work on the PMT was performed with a Hamamatsu picosecond light pulser which has a 100 picosecond wide half amplitude output. The PMT output was monitored on an oscilloscope for pulse shape and time information. With the closing of the Mt. Hopkins station, its field hardware set became available for use in Cambridge.

Using this data system, further tests could be run on the PMT's such that their operation could be better characterized and possibly improved. Also for these tests a light pulser was constructed such that the 3 nsec ruby laser could be simulated. This pulser consists of an avalanche transistor driven laser diode, configured such that changing the avalanche transistors energy storage capacitor would change the light output pulse width. Using this source, pulse widths of 3.5, 2.8, 2, and 1.5 nsec were now available along with the original 100 picosecond Hamamatsu pulser width.

Photocathode Illumination versus Transit Time Jitter

One of the major causes of transit time jitter is the differences in electron path length from the photocathode to the first dynode for electrons emitted from the center of the photocathode and those electrons emitted from the outer edge of the photocathode. The photocathode is a spherical surface to minimize the variation in path length but the various angles of emission of the electrons still give rise to an Amperex specification of 0.7 nsec transit time difference between the center of the photocathode and 18 mm from the center at a photocathode to first dynode bias of 430 volts.

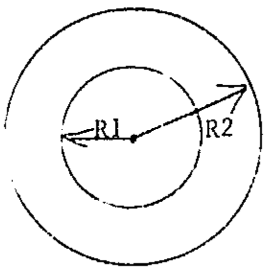
If a single electron can originate from any part of the photocathode then we would expect the total transit time jitter of the tube to be:

$$(X + Z)^{1/2} \qquad \text{EQ 1}$$

where X is the contribution from the electron path length differences and Z is caused by the spread in emission velocities of the secondary electrons. If the photocathode is apertured the total transit time jitter will be reduced.

In order to determine the optimum aperture size a test was run in which the transit time as a function of radial distance from the center of the photocathode was measured. The picosecond pulser was channeled thru a 1mm diameter fiber optic to the face of the PMT. The transit time was then measured at the photocathode center and at radial distances of 6, 12 and 18 mm (Figure 1).

If an aperture with Area A is placed over the photocathode and if the Area A is divided into two equal parts that are concentric, then a photoelectron from the inner area will have a shorter transit time with respect to a photoelectron from the outer area. Since the area's are equal the probabilities of generating the photoelectron will be equal.



$$A = \pi R_2^2 \quad \text{Area of Aperture}$$

$$A_1 = \pi R_1^2 \quad \text{Inner Area}$$

$$A_2 = \pi (R_2^2 - R_1^2) \quad \text{Outer Area}$$

want

$$A_1 = A_2$$

$$\pi R_1^2 = \pi R_2^2 - R_1^2$$

$$R_2^2 = 2R_1^2$$

$$R_1 = (2)^{1/2} R_2$$

Going back to EQ 1 and assume for the moment that Z is 0.4 nsec. We will pick a value for R_2 and then calculate R_1. Using this value of R_1 we will read off the value of X from Figure 1.

R (mm)	R (mm)	X (nsec)	RMS (nsec)
22	16	0.5	0.64
18	13	0.3	0.5
12	8.6	0.1	0.4

This simplified analysis states that the optimum aperture would have a radius of 12 mm or a diameter of one inch. Any further reduction in aperture would not decrease the jitter (as shown in the third example above).

Single photoelectron transit time JITTER was measured with the picosecond pulser for full photocathode illumination for a 12 mm diameter aperture and for a 3 mm diameter aperture. For full photocathode illumination the jitter was 0.61 nsec which agrees favorably with the calculated value of 0.64 nsec. For the 12 mm diameter the jitter was 0.39 nsec which also agrees with the calculated value of 0.4 nsec. Only one test was run with the 3 mm aperture which gave a jitter of 0.33 nsec. This value is low but certainly within the error limits of these tests.

The use of a one inch diameter aperture in the photoreceiver should present no problem since the minimum blur spot diameter is 6 mm with a 20 arc minute field (the largest field stop). Presently the photocathode is positioned such that the maximum spot size is 12 mm in diameter. An opaque plastic one inch diameter aperture mounted directly in front of the photocathode would insure that no stray photons would generate photoelectrons from the edge of the photocathode.

Range Noise Versus Source Pulse Width

In theory the range noise is a function of the source pulse width and the number of photoelectrons in the return. Assuming the returns are distributed normally, we have used the following expression as an indication of range noise:

$$RMS = 0.4\ PW\ (N) \qquad \text{EQ 2}$$

PW is the source pulse width at FWHA in nsec.

N is the number of photoelectrons in the return.

RMS is the range noise in nanoseconds.

In our recent field upgrading the transmitted laser pulse was reduced in width from 6 to 3 nanoseconds, which in turn improved our range noise by a factor of two.

One of the questions we addressed in our testing was: would further reduction in pulse width continue to decrease range noise and at what point would PMT transit time jitter overtake any decrease in pulse width.

The five plots (Figures 2-6) of range noise versus number of photoelectrons in the return show our results for various pulse widths. Figures 2 and 3 are for the 3 and 2.8 nanosecond source, representative of our current ruby laser pulse width. They show good agreement with the theoretical line except for some leveling off at the high photoelectron end. The range noise is down to about 0.15

nsec (2 cm) at this level and reflects the contribution of the electronics system to the range noise.

Figure 4 shows the results in using the picosecond source (100 ps FWHA). This would represent the minimum pulse width that mode selected lasers suitable for satellite ranging could produce. This data shows that the PMT transit time jitter is the limiting factor and that the lowest useful pulse width with this PMT system is about 1 nsec.

Figure 5 and 6 are for source widths of 2 and 1.5 nsec which represent the minimum pulse widths we could realistically obtain with our present ruby system (active Q switch and pulse chopper). These curves show reasonable agreement with the theoretical curves (derived from EQ 2), indicating that we would not be PMT limited in accuracy at these pulse widths.

Transit Time Versus Temperature

Even though the literature does not state that transit time depends on the temperature of the PMT, a quick test was run to verify this independence. The PMT was operated in its standard configuration with multiple photoelectron signals to decrease the jitter of the measurements. The dark current was monitored to determine the PMT temperature.

A data set was taken every 15 minutes as the tube was heating up for one hour. The resistors in the voltage divider string are the main source of heat. The dark current measurements implied that the internal temperature of the PMT increased by 2.5°C during this interval. The PMT was then heated with an external source to increase its temperature by another 13°C and the transit time was measured showing no change.

As the tube cooled down the transit time was measured and again showed no change.

An interesting observation about the results from this test is the stability of the system for a two hour period (Figure 7).

Transit Time Jitter Versus Bias Voltage

The single photoelectron transit time jitter should be a function of bias voltage. Since it is very difficult to measure this jitter at many different voltages, we took advantage of the fact that if the electron path length differences are minimized by the use of an aperture, then the width of the PMT output pulse is a direct indication of the transit time jitter. This is true because in this case the increase in pulse width is caused by the spread in the emission velocities of the secondary electrons. The pulse is further broadened by stray inductance and capacitance associated with the physical structure of the tube and base.

Single photoelectron output pulse half amplitude widths were measured as a function of bias voltage (see Figure 8). Using this data and the previous experimental result which showed the jitter to be 0.4 nsec at 2200 volts, a plot was generated which gives an estimate of the transit time jitter as a function of PMT bias voltage (see Figure 9).

Figure 1

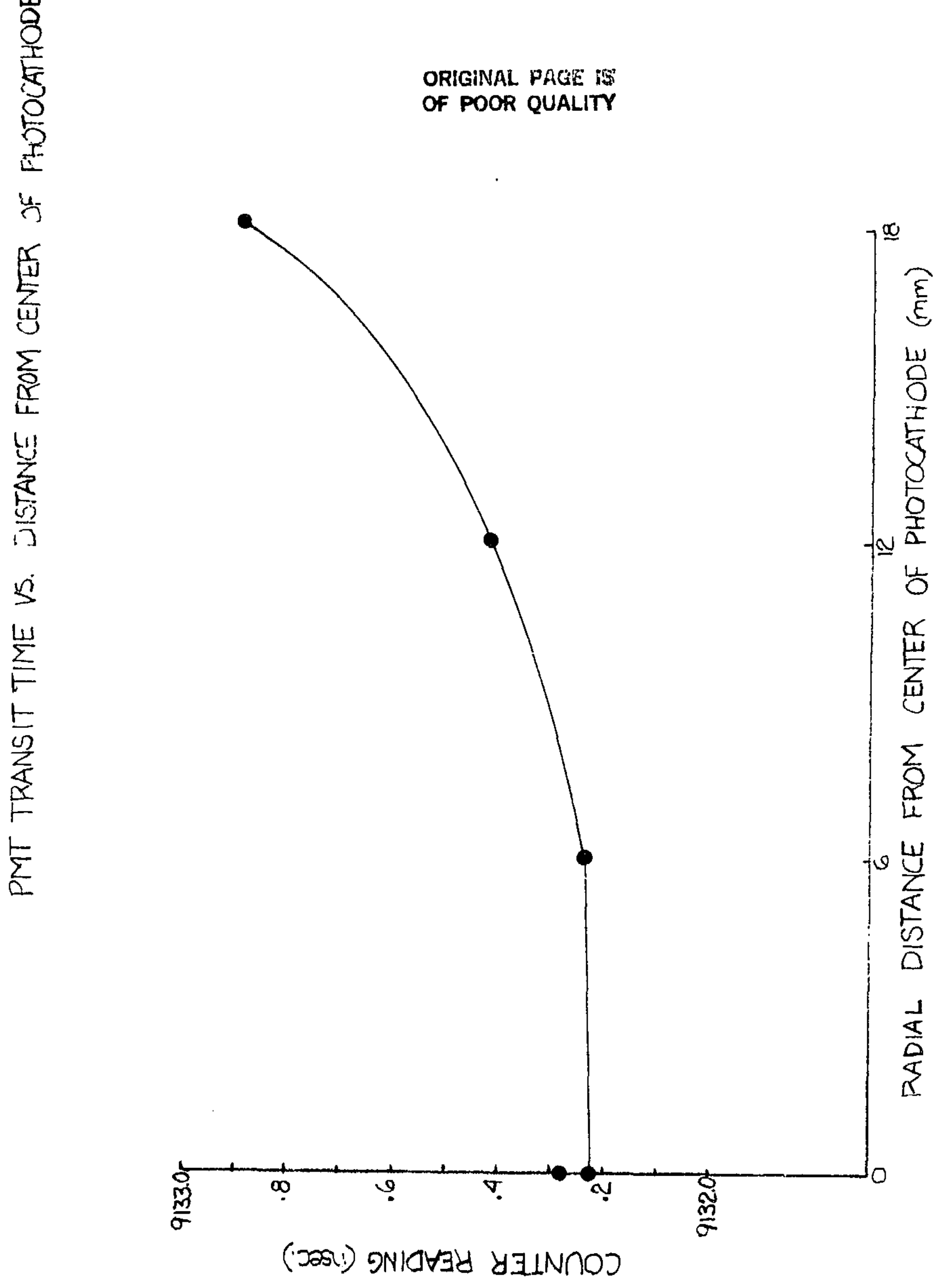

PMT TRANSIT TIME VS. DISTANCE FROM CENTER OF PHOTOCATHODE
ORIGINAL PAGE IS
OF POOR QUALITY
RADIAL DISTANCE FROM CENTER OF PHOTOCATHODE (mm)
0
6
12
18
COUNTER READING
9133.0
.8
.6
.4
.2
9132.0

Figure 2

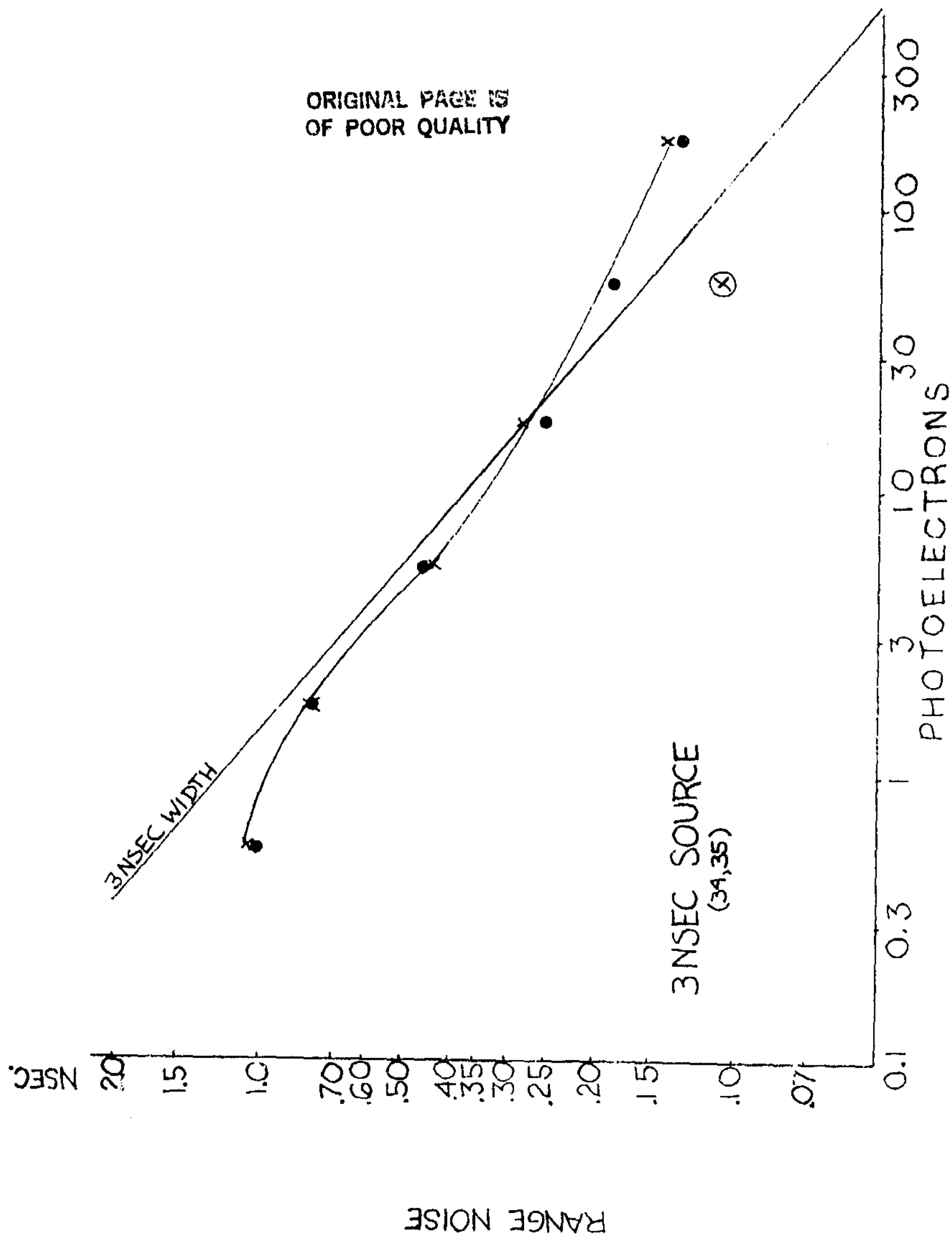

3NSEC WIDTH
3NSEC SOURCE
(34,35)
PHOTOELECTRONS
0.1
0.3
1
3
10
30
100
300
RANGE NOISE
NSEC.
2.0
1.5
1.0
.70
.60
.50
.40
.35
.30
.25
.20
.15
.10
.07

Figure 3

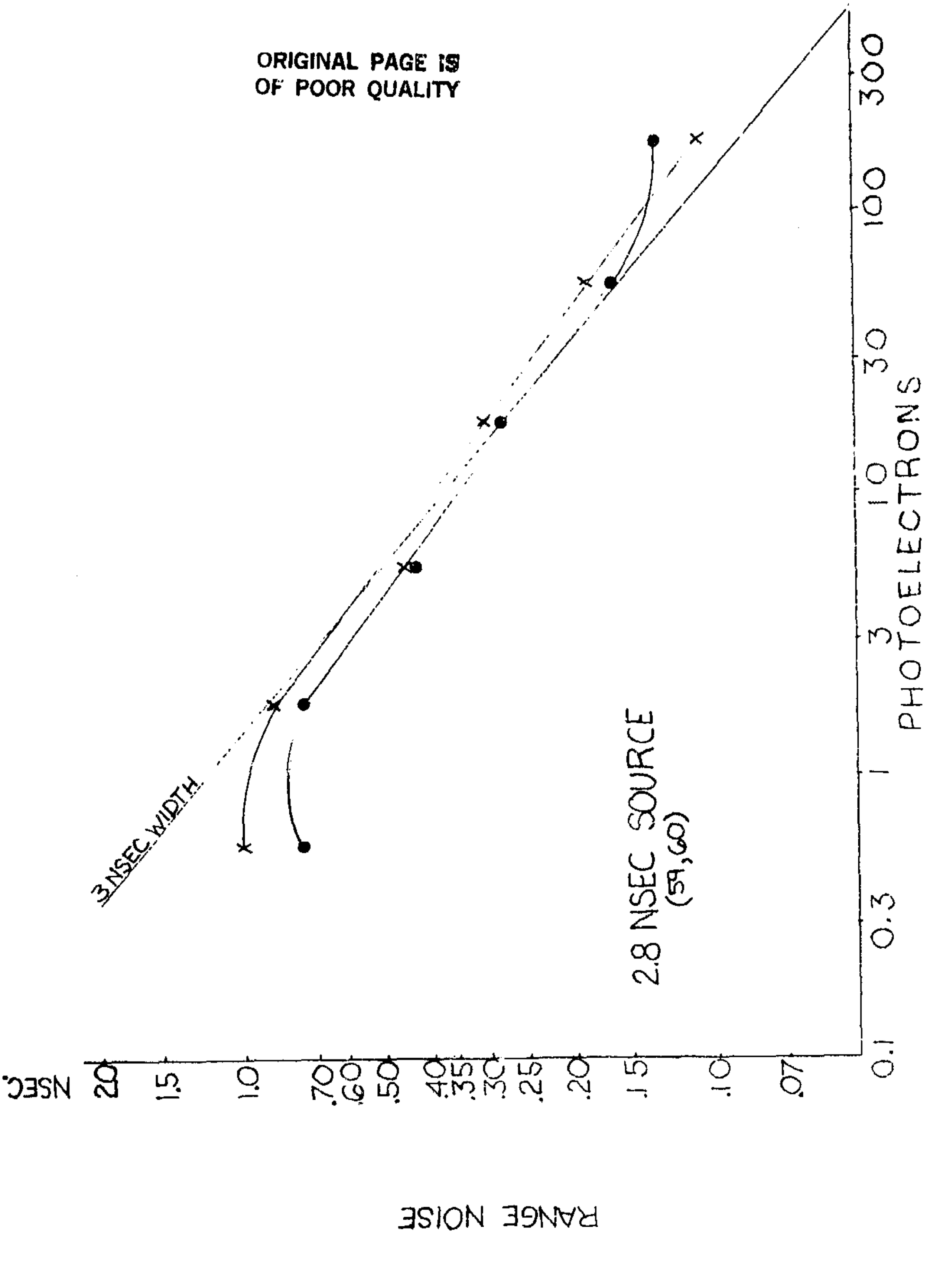

3 NSEC WIDTH
2.8 NSEC SOURCE
(59,60)
PHOTOELECTRONS
0.1
0.3
1
3
10
30
100
300
RANGE NOISE
NSEC.
2.0
1.5
1.0
.70
.60
.50
.40
.35
.30
.25
.20
.15
.10
.07

Figure 4

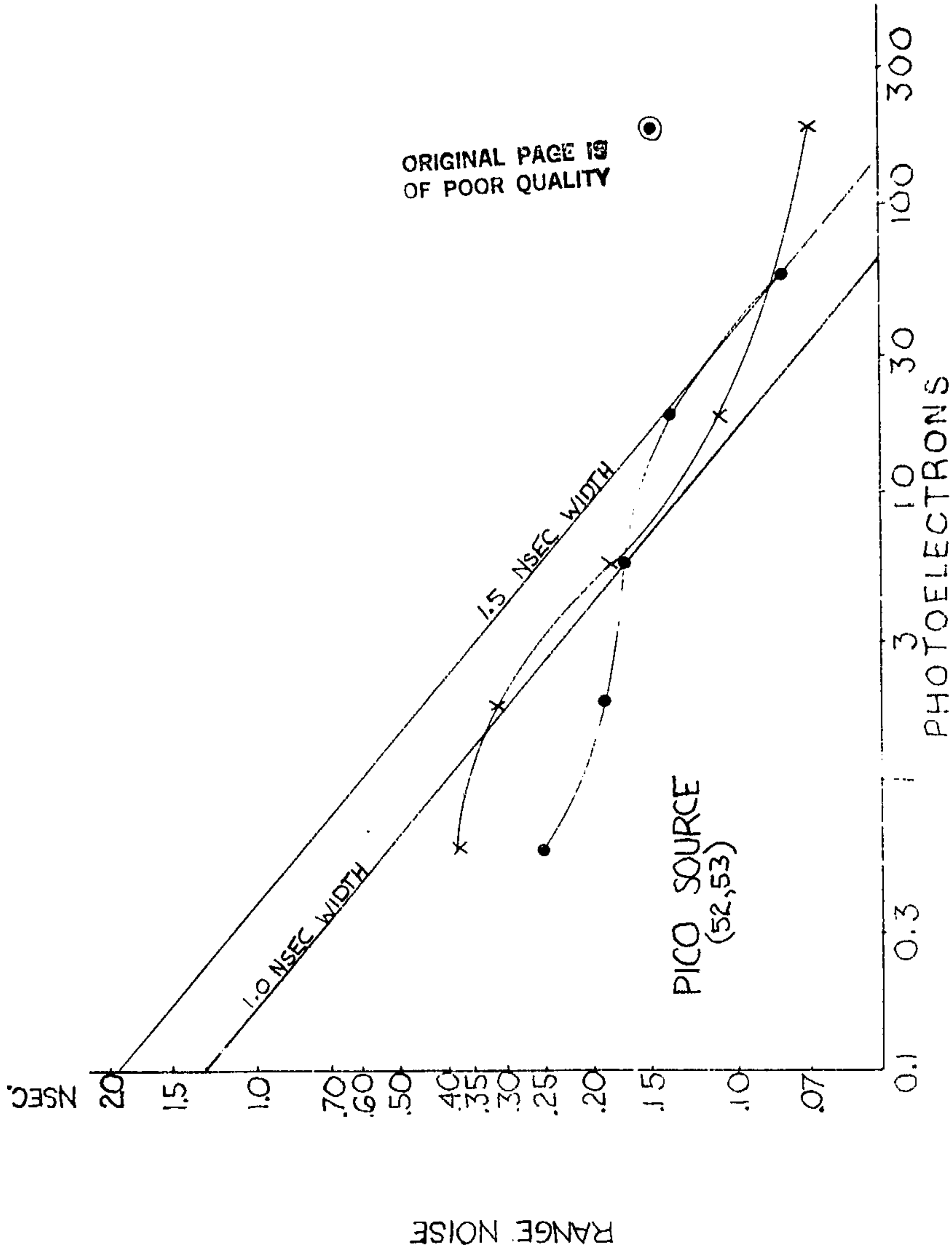

1.5 NSEC WIDTH
1.0 NSEC WIDTH
PICO SOURCE
(52,53)
0.1
0.3
3
10
30
100
300
PHOTOELECTRONS
NSEC.
2.0
1.5
1.0
.70
.60
.50
.40
.35
.30
.25
.20
.15
.10
.07
RANGE NOISE

Figure 5

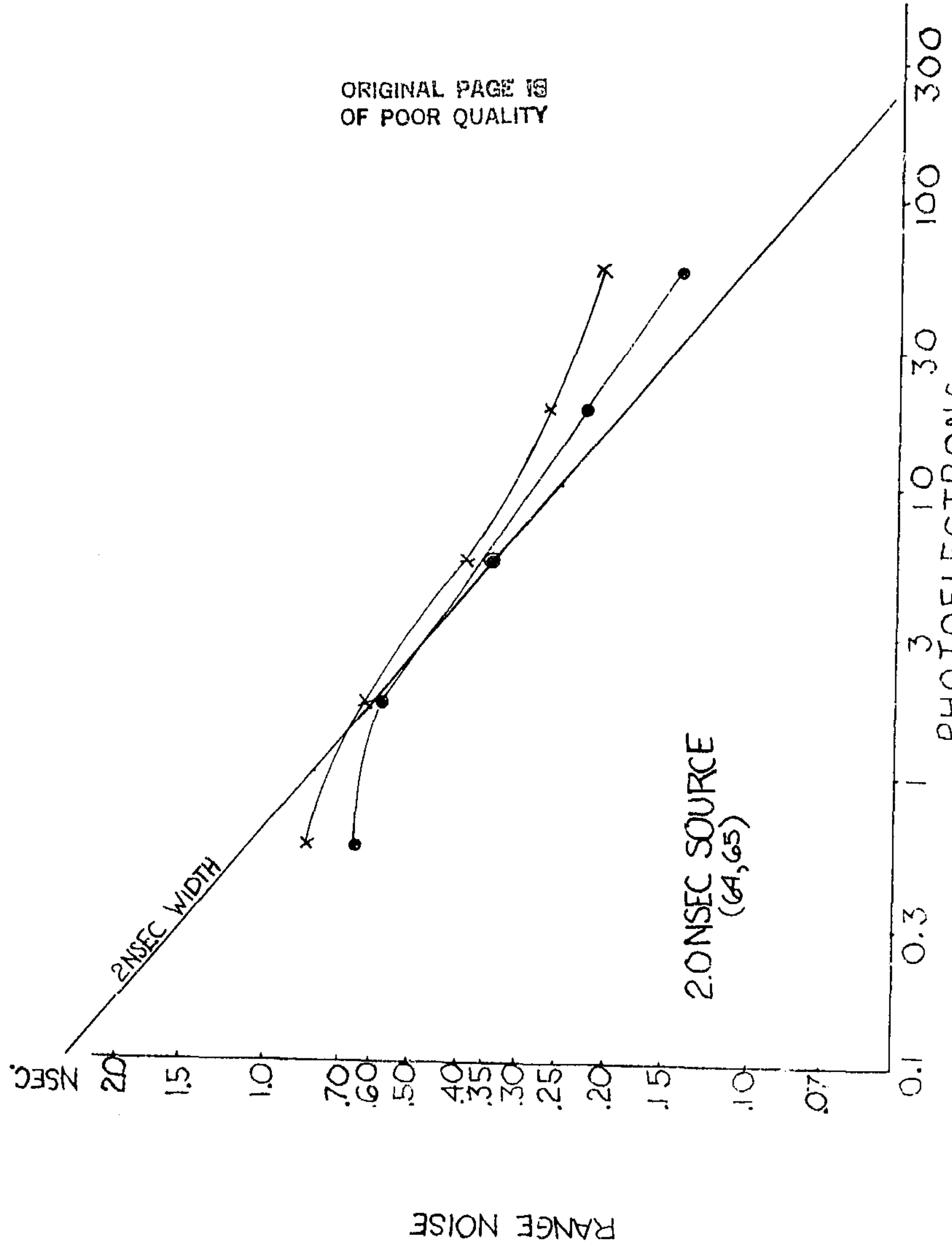

RANGE NOISE
NSEC.
2.0
1.5
1.0
.70
.60
.50
.40
.35
.30
.25
.20
.15
.10
.07
PHOTOELECTRONS
0.1
0.3
1
3
10
30
100
300
2NSEC WIDTH
2.0NSEC SOURCE
(64,65)

Figure 6

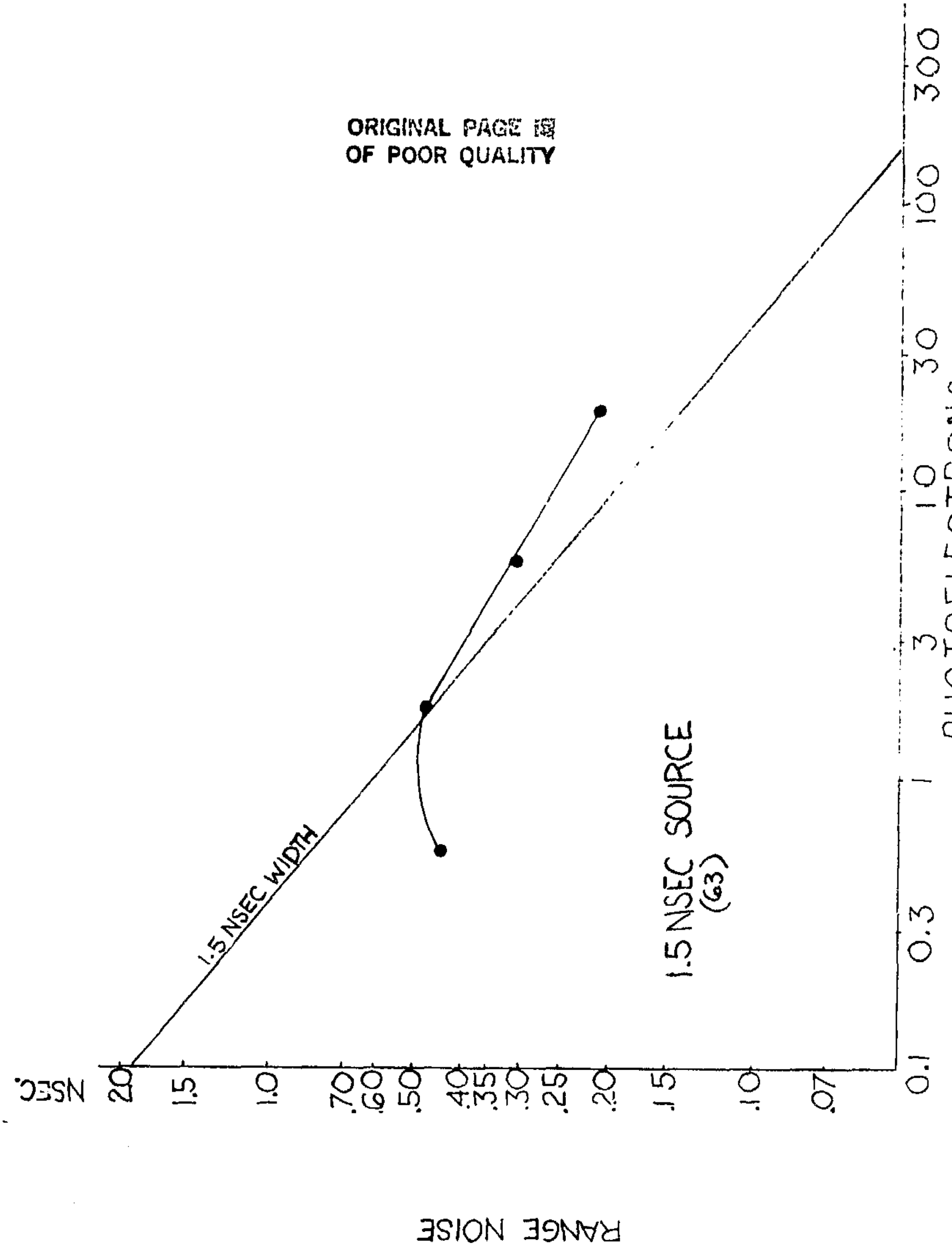
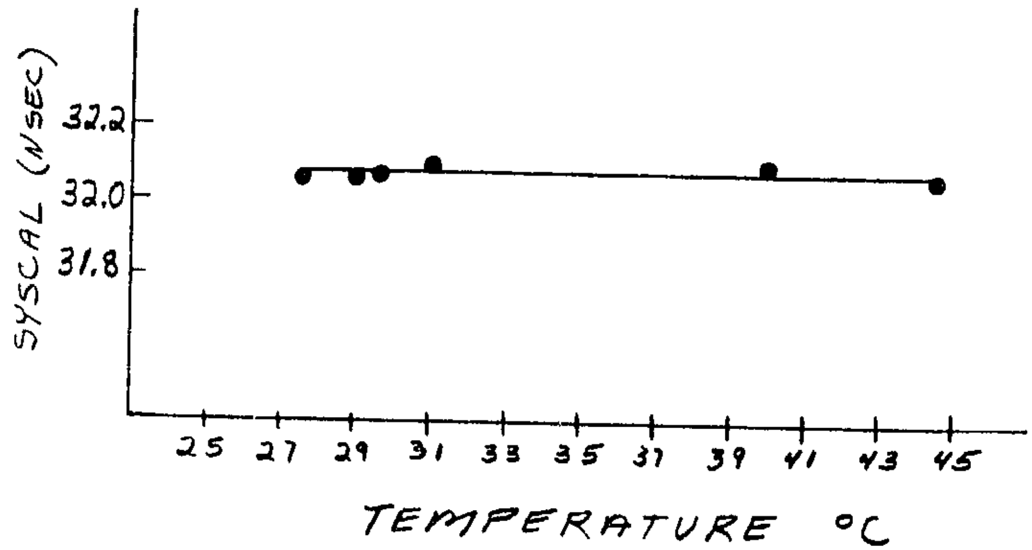

RANGE NOISE
NSEC.
2.0
1.5
1.0
.70
.60
.50
.40
.35
.30
.25
.20
.15
.10
.07
PHOTOELECTRONS
0.1
0.3
1
3
10
30
100
300
1.5 NSEC WIDTH
1.5 NSEC SOURCE
(63)

Figure 7

ORIGINAL PAGE IS
OF POOR QUALITY



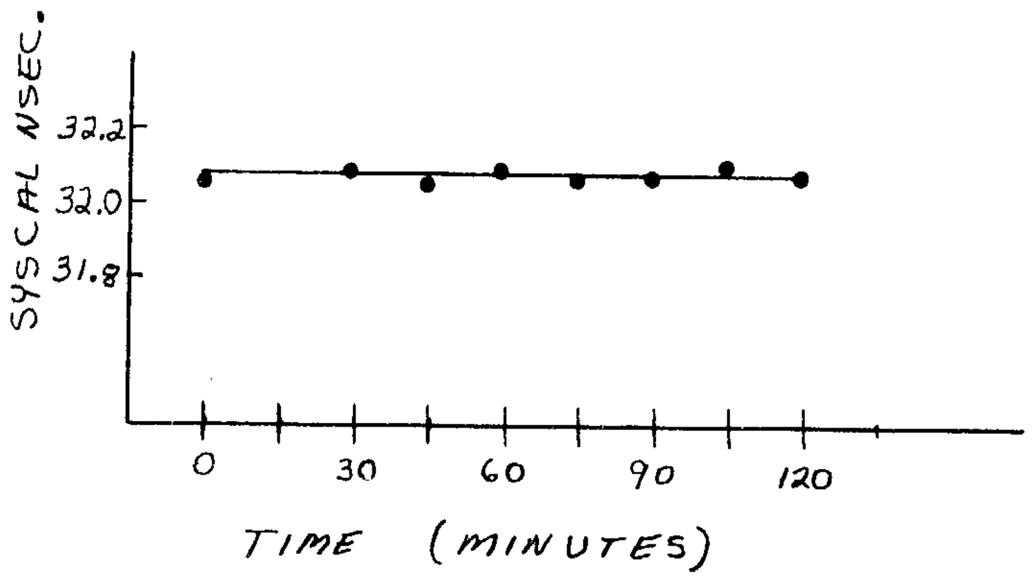
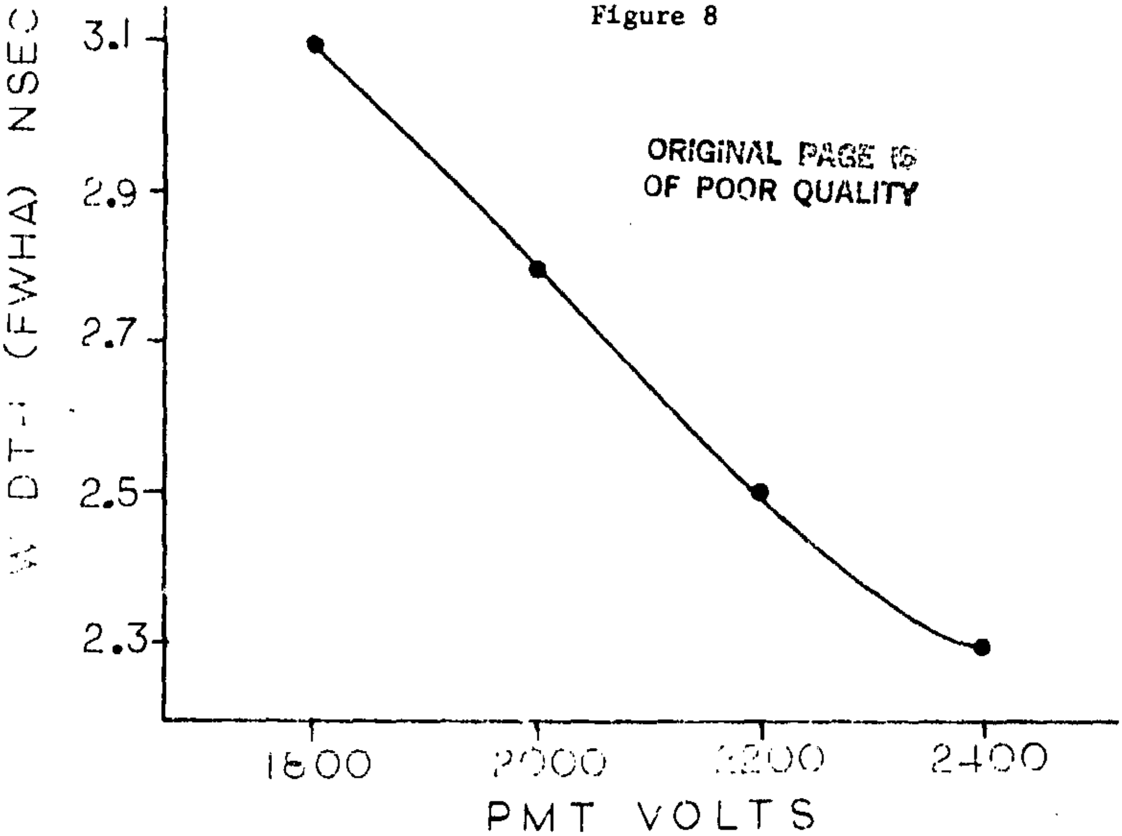
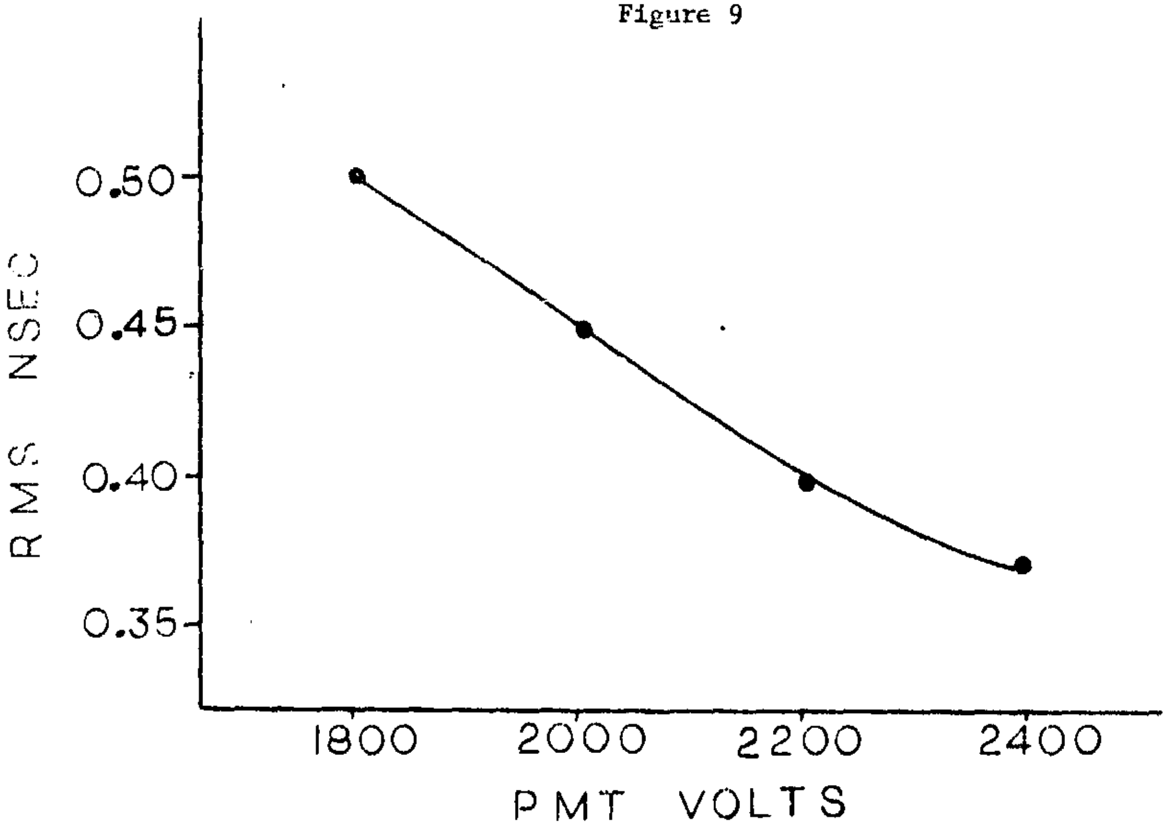


Figure 8



RMS PULSE WIDTH vs PMT VOLTAGE

Figure 9



Appendix 3

LASER SYSTEM CHARACTERIZATION

Prepared for the

NASA Satellite Laser Ranging
Configuration Control Board

by the
System Characterization Record Committee

June 1983

TABLE OF CONTENTS

ABSTRACT

A model is provided to help standardize the evaluation of laser ranging system performance in terms of ranging accuracy. The model deals with the magnitude and temporal nature of the known data error source and aggregates them in terms of Modelling (Environmental) Errors, Ranging Machine Errors, and Epoch (Timing) Errors. The model is provided to characterize and verify system performance for engineering, operations and data analysis requirements. It is anticipated that this model will be dynamic, evolving with our understanding and needs. An application of the model to the Arequipa station is included as an example.

LASER SYSTEM CHARACTERIZATION

1. REQUIREMENT AND METHODOLOGY

The Laser System Characterization is intended to provide a "Standard Error Model" to: (1) verify system performance, (2) verify system upgrading, and (3) compare systems. It certainly is not a substitute for collocation, but is a method of interim evaluation, and a means of isolating individual error source components.

The model should be used to characterize each system under normal operating conditions. That is, the model parameters should be tabulated for each operating system and then updated periodically on a regular basis and whenever a system undergoes maintenance or upgrading affecting the measurement path. The standard model also provides a format to characterize system performance under malfunctioning conditions, but its application to such a situation would have to be considered on a case by case basis. It may be more practical to disregard certain data than try to characterize data under conditions of equipment malfunctions or operator error.

In organizing this model, we placed requirements that it should:

1. Focus on the systematic error sources.
2. Specify the statistical means of characterizing each component (1 sigma, peak-to-peak, etc.)
3. Specify relevant time period or periods for each component.
4. Define a means of measuring and specifying each error component.
5. Specify a means of aggregating the error components.
6. Be practicable.

This model does not include the averaging effect derived through orbital geometry. Such averaging depends upon the method of analyses, the station configuration, and the geophysical parameters being sought. This model is intended to provide the analyst with the input required to test error sensitivity in his own application of data.

For convenience, we have divided the error components into three categories corresponding to the nature of the errors.

1. Ranging machine errors are those associated with the laser hardware and its calibration.
2. Epoch or timing errors are those associated with the station clock, or time and frequency transfer.

3. Modelling or environmental errors are those associated with data compensation for effects outside the ranging and timing system.

Even though the environmental errors are in some cases the results of models and are beyond the influence of a specific laser ranging group (i.e., space craft center-of-mass), they are included here for completeness, to give the data user the benefit of our knowledge about the data quality. The environmental and hardware errors are aggregated separately so that the reader can focus on his area of immediate interest.

The "Standard Model" should evolve and improve with our knowledge of the error sources. In particular, it is assumed that the models and techniques used to characterize the environmental effects will be replaced by new models as they are developed and accepted. It is also anticipated that archived data will be periodically reanalyzed as major improvements are introduced.

2. CLASSIFICATION OF ERROR SOURCES

The model components are divided into categories:

1. Modelling (Environmental) Errors
   a. Atmospheric Propagation (Model)
   b. Atmospheric Propagation (Meteorological Measurements)
   c. Spacecraft Center-of-Mass
   d. Ground Survey of Laser Position
   e. Data Aggregation

2. Epoch (Timing) Errors
   a. Portable Clock Set
   b. Broadcast Monitoring

3. Ranging Machine Errors
   a. Wavefront distortion (Spatial Errors)
   b. Uncorrected System Drift (Temporal Errors)
   c. Uncorrected Variation in system delay with Signal Strength
   d. Errors in target range or calibration path length
   e. Error in calibration due to uncertainties in meteorological conditions along the calibration path
   f. Variation in system calibration with background noise level
   g. Mount model influences

The user must be aware of the nature of each of the error sources, otherwise, he runs the risk of confusing an error source with a geophysical observable. This means that the operators of each laser ranging system must provide a determination of each error source (size and time constant) on a routine basis and make the full characterization schedule available to the users.

A comprehensive system evaluation must be made at least every six months and before and after each major modification to the hardware data flow path.

3. CHARACTERIZATION OF ERRORS

Each error source for each participating laser system must be characterized by its size and temporal nature. For simplicity, we use a one sigma representation for those components that appear random (such as wavefront) and one-half peak-to-peak for those effects that appear to have well defined trends (such as uncorrected variation with signal strength). This gives strong incentive to make analytic a posteriori corrections where possible.

Each error component has a characteristic signature in the pattern of residuals from a perfect orbit. In this model, the temporal nature of the error sources are quantified by time constants (decorrelation time) after which the pattern of residuals would change appreciably; it is assumed that the influence of error sources average out over 4-6 time constants. A specific component of error may decorrelate in steps owing to the various contributing activities.

In this model we characterize the error sources by their influence over specific integration periods which span the range of geophysical interest and operational constraints. In particular, we have chosen periods of: a pass, a day (several passes), a month, and many months (indefinite). These integration periods can of course be changed as dictated by requirements.

Many of the error sources, particularly those in the environmental category, almost certainly have variations with seasonal and annual periods. Once these effects are better understood and quantified, an annual time constant should be added to the model.

4. MODELLING ERRORS

A summary of the modelling errors appears in Figure 1, with notation whether they are determined (measured) on a site by site basis or estimated from general models in use.

4.1 Atmospheric Propagation Model

4.1.1 Model

The most frequently used model for columnar refraction between ground station and satellite is the Marini and Murray Model (Marini and Murray, 1973) based on radiosonde profiles. The use of this model should be standardized and changed only with the organized consensus of the community.

It must be recognized, however, that this model does not include the effects of horizontal gradients in atmospheric density. At low elevation angles, the laser beam may be passing through pressure fields that vary by a few millibars at ground level. This alone could introduce uncertainties as large as 1 cm or more. Even with no surface pressure changes with position, horizontal gradients in temperature can influence the model error for slant ranges by making the scale height depend on position. Gardner (1976, 1977) and Dunn et. al. (1982), have studied this effect and find typical errors of 1.5 and 2 cm (r.m.s.) respectively at 20 degrees elevation if no correction for horizontal gradient is made.

Since observations are taken over all accessible elevation angles (usually above 20 degrees), and since the effects of horizontal gradients fall off rapidly with elevation angle, the average effect is about 0.5 cm. In lieu of more definitive data at the moment, we have characterized the refraction error as 0.5 cm at 45 degrees elevation. Since atmospheric conditions typically change on both diurnal and longer timescales, we anticipate that the size of this error source would decrease slowly with observing time. In addition, there is probably an uncorrected an annual variation, but as yet this is unquantified.

4.1.2 Meteorological Measurement Error

The most significant term in the Marini and Murray Model is proportional to pressure. An error of 1 mb, which is common in todays field operations, will introduce an error of about 5 mm at 30 degrees altitude. However, it is quite feasible with available instrumentation to measure barometric pressure at field stations to 0.3 mb. To the extent that an error in pressure reading is due to instrument calibration or reading procedure, the influence of this component would be a long term range bias which increases with zenith angle and hence range. These errors should be estimated on a site by site basis by comparison with calibrated instrumentation.

CORRECTION	METHOD	ESTIMATED ACCURACY	TIME PERIOD	NATURE
ATMOSPHERIC PROPAGATION (MODEL)	MARINI AND MURRAY MODEL	0.5 CM (AT 45° ALT)	DAY; PROBABLY ANNUAL	BIAS (P.T.H.): VARIES WITH AZIMUTH AND ALTITUDE
ATMOSPHERIC PROPAGATION (MEASUREMENT)	MEASUREMENT OF P, T, H	DETERMINED	LONG TERM	OFFSET INCREASES WITH RANGE
S/C CENTER OF MASS (MODELS)	GSFC MODELS ARNOLD MODELS	2 MM	INDEFINITE (LONG TERM)	FIXED BIAS
GROUND SURVEY OF LASER POSITION (MEASUREMENT)	SURVEY MEASUREMENT	DETERMINED	INDEFINITE; PROBABLY ANNUAL	STATION POSITION ERROR
DATA AGGREGATION	AVERAGING 1-3 MINUTE DATA SEGMENTS	DETERMINED	PASS	DEPENDS ON DATA YIELD AND DISTRIBUTION

FIGURE 1
SATELLITE LASER RANGING SYSTEMS
MODELLING ERROR SOURCES

4.2 Spacecraft Center of Mass

The range correction to spacecraft center-of-mass for Lageos has been calculated analytically (Fitzmaurice et. al. 1978; Arnold 1978) and measured in the laboratory prior to launch (Fitzmaurice et. al. 1978). The analytical models show a dependence of range correction on pulse width and pulse detection scheme. For those situations in common the differences between the analyses by Fitzmaurice et. al. and Arnold is less than 1 mm. Our estimate for the error in range correction to Lageos is taken from the experimental measurement uncertainty which was about 2 mm (Fitzmaurice et. al. 1978). This value of course assumes that the correction made is appropriate for the laser pulse width and detection scheme. Otherwise, an error as large as 1 cm is possible. This error would be a long term fixed range bias.

4.3 Ground Survey of Laser Position

Lasers that reoccupy a site may not be placed in exactly the same position each time. As such the system reference point must be surveyed to the local geodetic reference marker. The error in this measurement will constitute a fixed offset in station position for the period of one site occupation. These estimates of measurement accuracy must be furnished by each laser ranging group for each occupation by a mobile laser system. In the case of fixed laser systems, the local survey errors is important from the standpoint of interconnecting datum, however, they do not effect direct measurement of station position or crustal motion. It should also be recognized that many ground sites have significant annual signatures due to changes in ground water. At some point, this issue must be systematically addressed.

4.4 Data Aggregation

Some of the ranging groups are now calculating aggregated data points (normal points) based on 1-3 minutes of range data. The aggregation schemes used have been verified to introduce errors of less than 1 mm in range. This error source probably depends upon data yield and data distribution, but likely has a time constant of the length of a pass or less. This component must be determined for the individual data aggregation technique. Once the technique has been standardized, this value would become a modelled parameter.

5. RANGING MACHINE ERRORS

The known ranging machine errors are summarized in Figure 2.

5.1 Spatial Variations

Spatial variations in time of arrival (or wavefront distortion) are the result of mode structure in the laser. Patterns in the far field tend to change appreciably over periods of a few hours or less, and hence the effect which can give a strong residual signature (depending upon mode pattern and satellite path within the laser beam) can vary from pass to pass. The effect tends to vary with pulse width and laser configuration.

SOURCE	DEPENDENCE	MEASUREMENTS	RELEVANT TIME PERIOD	COMMENTS
SPATIAL VARIATIONS (WAVEFRONT DISTORTION)	PROPORTIONAL TO PULSE WIDTH	MAP WAVEFRONT WITH CORNERCUBE	PASS OR SEVERAL HOURS	SYSTEMATIC RESIDUAL SIGNATURE (PASS); MAY AVERAGE OUT OVER SEVERAL PASSES
TEMPORAL VARIATION (UNCORRECTED SYSTEM DRIFT)	SYSTEM STABILITY INTERVAL BETWEEN CALIBRATIONS	STABILITY TEST RUN PRE-POST CALIBRATIONS	PASS (BETWEEN CALIBRATIONS)	REAPPEARING SYSTEMATIC TREND
SIGNAL STRENGTH VARIATION (UNCORRECTED VARIATION IN SYSTEM DELAY WITH SIGNAL STRENGTH)	PMT, PULSE AMPLITUDE AND WIDTH	CALIBRATE OVER FULL DYNAMIC RANGE	INDEFINITE (LONG TERM)	RANGE ERROR CORRELATED WITH SIGNAL STRENGTH (RANGE)
ERROR IN CALIBRATION TARGET DISTANCE (EXCLUSIVE OF METEOROLOGICAL EFFECTS)	SURVEY MEASUREMENT	SURVEY	INDEFINITE (LONG TERM)	FIXED BIAS
ERROR IN CALIBRATION MEASUREMENT	METEOROLOGY	P.T.H.	DAY, SEASONAL	BIAS WITH DIURNAL CYCLE AND SLOWER VARIATIONS
VARIATION WITH BACKGROUND LEVEL	PMT	CALIBRATE OVER RANGE OF ANTICIPATED CONDITIONS	DIURNAL	DIURNAL VARIATION
MOUNT MODEL	TRACKING ANGLES		INDEFINITE	SYSTEMATIC RESIDUAL SIGNATURE OVER A PASS; VARIATION IN INFLUENCE WITH SATELLITE ORBITAL GEOMETRY

FIGURE 2
SATELLITE LASER RANGING SYSTEMS
RANGING MACHINE ERROR SOURCES

Spatial variations are measured by mapping the wavefront with a fixed ground-based retroreflector. The effect would be characterized by the r.m.s. variation over the wavefront. Sufficient data must be taken to assure that range noise is negligible and there must be enough redundancy in the data taking sequence to verify the pattern (and avoid temporal effects).

5.2 Temporal Variations

Temporal variations refer to uncompensated system drift (change in internal delay) during ranging operations. These would be due to changes in temperature, cycling of fans and compressors, changes in line voltage, etc. The potential for a problem is exacerbated by increased time intervals between calibrations; systems that are calibrated on a pulse by pulse basis avoid the problem, whereas those that rely on pre-and-post pass calibrations must be very carefully monitored.

Temporal variations are evaluated on an r.m.s. basis by monitoring and analyzing pre-minus-post calibration differences over an extended period of time (at least one month). The pre-minus-post calibration is not unambiguously separable from meteorological fluctuations along the calibration path, (see below) but the method is simple and will give an upper bound to the effect.

Temporal variations can also be monitored by ranging to a close ground target (to minimize propagation effects) over a period of several hours.

5.3 Signal Strength Variations

Variations in system delay with signal strength arise because performance of devices within the system including PMT's are amplitude and/or pulse-width dependent. Those systems that operate at the single photoelectron level only would have very minimum degradation due to this effect.

The variations with signal strength, which are measured by detailed target calibrations over the full dynamic range of the system, tend to have a systematic trend which may lend itself to a posteriori analytic correction. Since this error source is dependent upon signal strength and hence range, it can give systematic residual patterns. As such, the effect is long term. As an incentive to consider analytic corrections, this model uses a one-half peak-to-peak representation (over the pertinent dynamic range) to characterize this effect.

5.4 Calibration Target Distance

5.4.1 Measurement Techniques (Exclusive of Meteorological Correction)

Error in calibration target distance includes both ground targets and internal calibration paths. This is essentially how well a path can be measured by ground survey or tape measure. Each station must provide an estimate of target range accuracy which is based on the measurement technique. This error is a fixed long term bias.

In addition, as mentioned in 4.3 above, each station may have a significant annual signature in the distance between the laser and the ground target. Ideally, target distance should be measured seasonably to determine: (1) if such a variation exists; (2) if it is significant and reproducible, and, (3) if a useable model can be developed.

5.4.2 Meteorological Correction to Calibration

In those systems that use ground targets for calibration, corrections must be made for horizontal propagation delay. The technique for computing this correction should be standardized to the group refractivity (Ng) derived from the Barrel and Sears formula adopted by the IAG in 1963.

$$Ng = N - \lambda \frac{dN}{d\lambda} = 80.343\ f(\lambda)\frac{P}{T} - 11.3\frac{e}{T}$$

where:

$$f(\lambda) \equiv 0.9650 + \frac{0.0164}{\lambda^2} + \frac{0.000228}{\lambda^4}$$

which has been normalized to 1 for λ = 6943Å (ruby laser wavelength)

and where:

λ = wavelength in microns

P = total air pressure (mb)

e = partial pressure of water vapor (mb)

T = temperature (degrees Kelvin)

The refractive correction should be based on measurements of P and T at both ends of the calibration path or in the very least, an extrapolation based on the slope of the calibration path.

The total effect of the atmosphere is about 270 parts in 10^6 at sea level. The major uncertainties in making this correction are temperature and pressure variations along the path. This effect probably includes short period terms which average out over time spans of a day plus longer term biases which may include seasonal and even annual effects.

Fluctuations of several degrees, which are not uncommon over a 1 km path can lead to an error in the refraction correction of as much as 1% (3mm). The size of the annual component is not clear, but it may be significant.

Instrument and procedural errors in the reading of pressure and temperature also add uncertainties to the refraction correction. A reading error of 1 mb in pressure or $0.5^{\circ}C$ in temperature will introduce a bias error of .1% in the refraction correction (or about .3 mm for a 1 km calibration path).

The value of the error (r.m.s.) in the meteorological correction must be determined by each station based on local measurements, topography, and instrument calibration.

5.5 Mount Model Influence

Mount eccentricities can produce pass-dependent systematic range errors. The pertinent eccentricities must be measured and/or modelled with appropriate range error characteristics. The influence of this effect is of particular importance with large instruments and with X-Y mounts. Since mount eccentricities produce reproducible, systematic components, the unmodelled (uncompensated) effects should be estimated on a half peak to peak basis.

5.6 Variation with Background Noise Level

There is some speculation that system delay may be a function of background noise level. However, to date there has been no verification of this effect.

6. TIMING ERRORS

The standard epoch reference used for laser ranging is UTC (USNO). The accuracy to which epoch is maintained is station dependent and must be furnished by each operating station. In practice, all station clocks are checked periodically with a portable clock and monitored at least once per day using LORAN, GPS, TV Reception, VLF or some other broadcast source. On a single pass basis with Lageos, a 1 microsec epoch error will introduce an error in station position of about 4 mm.

6.1 Portable Clock Check

Portable clock checks are typically of .1-1.0 microsec quality depending upon the portable clock, the length of the clock trip, and the station clock. An error in the portable clock set introduces a fixed bias component (long term) until a subsequent clock trip takes place.

6.2 Time Broadcast Monitoring

Epoch and/or frequency broadcasts are monitored at least daily by most operating stations. Those that receive TV line signals, or ground wave LORAN should be able to monitor epoch to 1 microsec; GPS reception should be considerably better. The daily values are independent determinations of station clock offset and hence the time constant for this component of epoch error is one day. For those using skywave LORAN or VLF, daily fluctuations of several microseconds due to propagation effects are common. In this case, averaging over several days is required to smooth out the data. The time constant in this case is 3-5 days. Routine monitoring of VLF propagation by the U.S. Coast Guard indicates that long term (even annual) variations measured during periods of stable propagation during the day are typically 1 microsecond or less.

It should be pointed out that historically long term timing errors have been notorious at the field stations. For the most part however, these have been the result of hardware and/or operational difficulties which should be documented as malfunctions.

7. AGGREGATION OF ERRORS

Since the nature and representation of the separate error sources is quite varied a rigorous aggregation of the error sources would be quite difficult. However, a simplified approach to data aggregation is to assume that the individual components of error are uncorrelated and that an r.s.s. of all pertinent error sources is sufficient to give an overall estimate of total ranging error. For this, we would form separate estimates of range error for each integration (averaging) time of (1) a pass, (2) a day, (3) a month, and (4) an indefinite period (long term).

As pointed out earlier, once the annual components are better understood, they should be tabulated separately. An example of how the data could be presented and aggregated is shown in Figure 3. An example using the SAO laser in Arequipa is shown in Figure 4.

8. AN EXAMPLE: THE AREQUIPA LASER

The "Standard Error" Model for the Arequipa Laser appears in figure 4.

8.1 Environmental Errors

8.1.1 Atmospheric Propagation Model

We use the Marini and Murray Model for the atmospheric propagation correction to satellite ranges. We estimate the refraction error to be 0.5 cm (see above). With our ground based meteorological instruments we read barometric pressure with a mercury column to an estimated accuracy of ± 1 mbar based on a comparison among instruments.

RANGING ERRORS (CM)

	PASS	DAY	MONTH	INDEF.
MODELLING (ENVIRONMENTAL) ERRORS				
ATMOSPHERIC PROPAGATION (MODEL)				
ATMOSPHERIC PROPAGATION (METEOROLOGICAL MEASUREMENTS)				
SPACECRAFT CENTER OF MASS				
GROUND SURVEY OF LASER POSITION				
DATA AGGREGATION				
R.S.S.				
RANGING MACHINE ERRORS				
SPATIAL VARIATION				
TEMPORAL VARIATION				
SIGNAL STRENGTH VARIATION				
CALIBRATION PATH (SURVEY)				
CALIBRATION PATH (METEOROLOGICAL CONDITIONS)				
MOUNT MODEL				
R.S.S				

RANGING ERRORS (CM)
TIMING ERRORS (MICROSEC)

PORTABLE CLOCK SET				
BROADCAST MONITORING				
R.S.S.				

FIGURE 3
ESTIMATED RANGING ERRORS FOR
SATELLITE LASER RANGING SYSTEM

RANGING ERRORS (CM)

	PASS	DAY	MONTH	INDEF.
MODELLING (ENVIRONMENTAL) ERRORS				
ATMOSPHERIC PROPAGATION (MODEL)	0.5	0.5	0.5	0.5
ATMOSPHERIC PROPAGATION (METEOROLOGICAL MEASUREMENTS)	0.5	0.5	0.5	0.5
SPACECRAFT CENTER OF MASS	0.2	0.2	0.2	0.2
DATA AGGREGATION	-	-	-	-
GROUND SURVEY OF LASER POSITION	-	-	-	-
R.S.S.	0.7	0.7	0.7	0.7
RANGING MACHINE ERRORS				
SPATIAL VARIATION	3.0	2.0	1.0	1.0
TEMPORAL VARIATION	2.0	1.0	1.0	1.0
SIGNAL STRENGTH VARIATION	3.0	3.0	3.0	3.0
CALIBRATION PATH (SURVEY)	1.0	1.0	1.0	1.0
CALIBRATION PATH (METEOROLOGICAL CONDITIONS)	0.9	0.9	0.9	0.9
MOUNT MODEL	0.1	0.1	0.1	0.1
R.S.S	4.9	4.0	3.6	3.6

TIMING ERRORS (MICROSEC)

PORTABLE CLOCK SET	1.0	1.0	1.0	1.0
BROADCAST MONITORING	4.0	4.0	1.0	1.0
R.S.S.	4.2	4.2	1.4	1.4

FIGURE 4
ESTIMATED MEASUREMENT ERRORS FOR THE AREQUIPA
SATELLITE LASER RANGING SYSTEM

8.1.2 Spacecraft Center-of-Mass

SAO uses the Arnold Models for its spacecraft center-of-mass corrections. The correction used for Lageos on the Arequipa data is 24.3 cm. This is appropriate for a 3 nsec pulse and a centroid (center of gravity) detector. The estimated error is 2 mm (r.m.s.).

8.1.3 Ground Survey of Laser Position

Since the Arequipa laser is a fixed system, no error for ground survey of laser position is included.

8.1.4 Data Aggregation

We do no aggregation on the quick-look or final data.

8.1.5 Summary of Environmental Errors

The aggregated environmental contribution is estimated at 1.6 cm over the short term (a day or less) and 1.2 cm for longer periods.

8.2 <u>Ranging Machine Errors</u>

8.2.1 Spatial Variations

Spatial variations are measured in Arequipa by ranging on a ground-based corner cube at a distance of about 1 km. Range measurements are made in sets of 50-100 laser shots at return signal strengths in the range of 5-20 photoelectrons. Measurement sets are taken over a matrix with 20 arcsec spacings over the 2 arcmin wide laser output beam. The sets are taken in random order around the matrix with scheduled returns to the central "reference" position to check for temporal drift. The mean values of the sets are used to map the wavefront contours and to calculate the r.m.s. wavefront variation.

The r.m.s. spatial variation in Arequipa is typically in the range of 2-3 cm. Experience has shown that the wavefront pattern changes appreciably over a period of a day. We use a value of 2 cm for the daily average to accommodate the fact that the acquired Lageos pass in a given day may come within a few hours of each other. Examination of wavefront data over extended periods of time indicates that over the long term, the effect averages to zero for this ranging system. However, since the resolution of the Arequipa system is about 1 cm, we use this value (1 cm) for our long term estimate of error.

8.2.2 Temporal Variations

An upper bound for the temporal variations have been estimated from the historical pre- and post-calibrations (which are taken on the billboard target before and after each pass). In pre- and post-calibrations at least 50 laser measurements are taken to the ground target in the return signal strength range of 5-25 photoelectrons. Mean values for each are

calculated; the pre-post difference for each pass is used to bound the system drift over the pass time duration. These differences, which have typical r.m.s. values of 2 cm, show no systematic trend over a period of several months, indicating that temporal variations (if they are at all significant) average out very quickly. Once again, due to the limitation in system resolution, we estimate the long term error component for temporal variations at 1.0 cm.

8.2.3 Signal Strength Variations

In Arequipa, the system delay variation with signal strength is measured routinely with extended calibrations on the billboard target. Measurements are taken over the range of 1 to 100 photoelectrons by adjusting neutral density filters in the photoreceiver. Sufficient data are taken to ensure that at least a hundred returns are received at the single photoelectron level and at least 25-50 returns are received in each half decade interval over the return energy range (the actual set size is made sufficiently large to reduce the statistical errors (1 sigma) to about 1 cm). The data are aggregated in corresponding signal strengths sets to examine system performance. Typical variations over the full dynamic range are 3 cm or less (half peak-to-peak). As a rule, system calibration value increases with signal strength, but point by point fluctuations make it difficult to model and correct.

8.2.4 Calibration Target Distance

The target distance in Arequipa is about 1 km along a nearly horizontal path. The target distance is measured with a laser geodimeter (Hewlett Packard Model 3808A) which has an accuracy of about 1 cm. The distance is measured repeatedly over the period of a day to average out statistical errors. Propagation corrections are made using the Barrel and Sears formula. At the moment we measure temperature and pressure only at the ranging site. We anticipate fluctuations of a few degrees (Celsius) along the path giving an uncertainty of about 1% or 3 mm. It is not clear how much of this is short term and how much is seasonal. At the moment we assume that this is a long period effect. We use a Mercury column to measure pressure and a standard mercury thermometer to measure temperature. In addition, a reading error of 1 mb and 0.5°C which could add another .6 mm in long term bias error.

8.2.5 Mount Model

The eccentricity of the mount in Arequipa has not been measured but on the basis of the compact design of the Azimuth-Altitude Mount and the separated laser and photoreceiver we estimate the eccentricity at 1 mm or less.

8.2.6 Summary of the Ranging Machine Errors

The aggregated ranging machine errors amount to about 5 cm on a single pass basis, and about 3.6 cm over the long term.

8.3 Timing Errors

The timing system at the Arequipa station uses redundant clocks (with Cesium and Rubidium Standards), VLF, Omega and portable clock checks. The accuracy of portable clock sets as determined from closure is typically 1 microsecond (r.m.s.) or better. The portable clock readings indicate that station time continuity over the short term (single pass) as maintained by VLF phase reading to be better than ±4.0 microseconds. Based on our experience and that of the U.S. Coast Guard in monitoring VLF, it appears that data smoothing reduces this error considerably over a few days.

The long term bias is assumed to be 1 microsecond which is typical of U.S. Coast Guard measurements.

cc: System Characterization Record Committee:

Dave Edge/Bendix
Wayne Hughes/GSFC
Tom Johnson/GSFC/TLRS-2
Henry Linder/GSFC/DIS
Lou Macknik/UHawaii Hollas
Randy Ricklef/UTex/TLRS-1 MLRS

Peter Bender/UColorado
John Bosworth/GSFC
Robert Coates/GSFC
Steve Cohen/GSFC
Charles Finley/NASA
Ben Greene/NATMAP Australia
James Maddox/SAO
Peter Morgan/NATMAP Australia
Robert Schutz/UTexas
David Smith/GSFC
Chris Stephanides/GSFC
Byron Tapley/UTexas
John Thorp/SAO
Peter Wilson/IFAG Germany

C-2

AGREEMENT

between

SMITHSONIAN ASTROPHYSICAL OBSERVATORY
OF THE UNITED STATES OF AMERICA

and

CONSIGLIO NACIONALE DELLE RICERCHE (CNR)
OF ROMA, ITALY

for the

SET UP AND OPERATION OF A
SATELLITE LASER RANGING SYSTEM

This agreement, entered into this______day of ___________1982 by the Smithsonian Astrophysical Observatory, hereinafter referred to as SAO, and the Consiglio Nacionale delle Ricerche, hereinafter referred to as CNR, does WITNESS that parties hereto agree as follows:

SAO RESPONSIBILITIES

Station Set up

On a cost reimbursement* basis SAO will:

1. Pack and ship a fully operational laser ranging system to the agreed site.

2. Provide the latest field software in use with the other SAO lasers.

3. Provide the necessary manpower to set up the laser and upgrade the system as per the latest SAO modifications (already installed at Arequipa and Mt. Hopkins).

4. Provide manpower, on an interim basis as agreed, to train Italian personnel at the site and to assist in the transition to a fully operational station. It is anticipated that this will require a maximum of 2 man months after the laser is operational.

5. Provide on site training in Cambridge and at a field station for two CNR representatives.

Station Operations

Within the constraints of NASA support SAO will, on a best efforts basis:

1. Provide on an operational basis orbital elements in the appropriate format for laser pointing predictions.

2. Provide routine data review and engineering/operations assessment reports on a timely basis.

3. Provide headquarters support in terms of scheduling, priorities, and network coordination.

4. Provide designs for any future hardware upgrades that are applied to the SAO lasers, providing hardware when requested on a cost reimbursement* basis.

5. Provide any future software modifications and upgrades that are applied to the SAO lasers.

6. Provide repair and maintenance service on a cost reimbursement* or trade basis as appropriate on hardware, components, systems, and subsystems.

7. Provide Field Engineering support on a cost reimbursement* basis.

8. Provide reformatted final data from linc tape to industry compatible magnetic tape on a routine basis and/or provide the SAO software to perform the reformatting process.

CNR RESPONSIBILITIES

Station Set Up

CNR will make its best effort to:

1. Provide a building design agreeable to SAO.

2. Prepare the site and building as necessary to accommodate the laser system.

3. Assume all costs for station set up items above.

4. Provide all necessary administrative assistance to SAO personnel entering and leaving Italy.

5. Provide sufficient manpower and local support and resources to set up the station.

Station Operations

CNR will make its best efforts to:

1. Operate the station as per the NASA-CNR agreement (specified in a letter from M. G. Finarelli to L. Guerriero dated November 24, 1981).

2. Make all quick-look and final data available to SAO on a punctual basis as agreed.

3. Provide operations and configuration control as per NASA Laser Tracking Network requirements.

*CNR will reimburse SAO for travel, transportation, local expenses for field personnel, and local purchases of goods and services.

It is intended that this agreement should be in consonance with and subordinate to the NASA-CNR agreement of 29 November 1981 with SAO acting on behalf of NASA.

It is understood that the ability of SAO and CNR to carryout their respective obligations is subject to availability of funds, and in the case of SAO, the concurrence of NASA.

SAO and CNR agree that, with respect to injury or damage to persons involved in operations undertaken pursuant to this agreement, neither SAO nor CNR shall make any claim with respect to injury or death of its own or its contractors' or its subcontractor's employees or damage to its own or its contractors' or its subcontractors' property caused by activities arising out of or connected with this project, whether such injury or damage arises through negligence or otherwise.

This Agreement shall remain in force and effect from the date of its execution for an indefinite period of time, however it may be terminated by either CNR or SAO at any time by giving a one hundred twenty (120) day advance written notice of termination to the other party.

IN WITNESS HEREOF, the Smithsonian Astrophysical Observatory and the Consiglio Nacionale delle Ricerche have caused this Agreement to be signed and sealed in duplicate.

SMITHSONIAN ASTROPHYSICAL OBSERVATORY	CONSIGLIO NACIONALE DELLE RICERCHE
Signature	Signature
JOHN G. GREGORY Contracting Officer Name and Title	Name and Title
Nov. 8 1982 Date	Date